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Acurex Corp, Mountain View, Calif Aerotherm Group

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Wet-packed scrubber, jet engine clean combustor, and ferrocene fuel-additive test cell emissions control strategies are described. Clean combustor technology and its associated cost of implementation are discussed in detail. Wet-packed scrubber construction cost estimates are also examined in detail. These control methods probably reduce jet engine test cell plume opacity below local regulations. However, based on limited data, it is estimated that for some jet engine tests, applying clean combustors can cause NO_x emissions to rise above local stationary source regulations. The air quality impact of controlled jet engine test cell emissions is small.

Jet engine and test cell emissions data collected during this study are summarized in this document.

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Background information is provided on the environmental aspects of uncontrolled and controlled military jet engine test cell operations. The environmental impact of these operations is considered on both a source and an air quality basis. Some of the uncontrolled jet engine test cell exhaust plumes exceed local opacity regulations for stationary sources. However, the air quality impact of uncontrolled operations is small.

Wet-packed scrubber, jet engine clean combustor, and ferrocene fuel-additive test cell emissions control strategies are described. Clean combustor technology and its associated cost of implementation are discussed in detail. Wet-packed scrubber construction cost estimates are also examined in detail. These control methods probably reduce jet engine test cell plume opacity below local regulations. However, based on limited data, it is estimated that for some jet engine tests, applying clean combustors can cause NO_x emissions to rise above local stationary source regulations. The air quality impact of controlled jet engine test cell emissions is small.

Jet engine and test cell emissions data collected during this study are summarized in this document.

SUMMARY

The Navy, Air Force, and Army test jet engines in test cells as part of routine maintenance procedures. When tested, some jet engines produce a dark particulate test cell exhaust plume which is visible from a distance. Recently, several military jet engine test cell facilities have been cited for violation of local air pollution control district stationary source opacity regulations. This study documents the results of the second phase of a two-phase effort to provide background information to the Stationary Source Enforcement Division of the Environmental Protection Agency on jet engine test cell emissons and their control.

Jet engine clean combustor technology was examined as a means of controlling jet engine test cell exhaust emissions, and plume opacity. Considerable progress has been made in civilian jet engine clean combustor technology. Gaseous emissions have been reduced, while exhaust opacity is maintained at very low levels. Military jet engine clean combustor technology has produced several afterburning and nonafterburning jet engines with virtually invisible exhausts. Because of sparse data and variability with engine model, the impact of military engine clean combustor technology on gaseous emissions is not clear. The only consistent trend in the gaseous emission data indicates that NO_x emissions are increased when smokeless clean combustors are incorporated into military jet engines.

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Performance and durability goals for military jet engines make it difficult to simultaneously reduce all emissions and exhaust opacity by applying clean combustor technology to new engines. Further, it is even more difficult to reduce emissions and opacity by retrofitting clean combustors to existing jet engines. However, the military now has a smoke standard for all new engines and goals for lower emission levels have been established for future engine procurements. The setting of smoke standards and emission goals and the successes of the civilian and military clean combustor programs are encouraging evidence that future military jet engines will be cleaner than existing engines.

Several existing military jet engines have been made clean by retrofitting clean combustors. Some engines originally scheduled to be retrofit have not been altered. This is primarily due to problems in meeting performance and durability goals, difficulties in achieving adequate designs for reducing emissions and retirement schedules which make retrofitting some older engines economically unjustifiable.

Currently, 28 percent of the Air Force and 40 percent of the Navy jet engines are smokeless. By retrofitting old engines with clean combustors, procuring new clean engines, and retiring old smoky engines, it is expected that 40 percent of the Air Force engines will be smokeless by 1984 and 65 percent of the Navy engines will be smokeless by 1985.

In the Phase I study, three widely different wet-packed scrubber control device cost estimates were received from the Navy and a private contractor. These estimates were examined in detail to identify the source of the difference and to determine if a single representative cost estimate could be derived from the three estimates. Investigation showed that the wide variations in the estimated costs were the result of assuming different baseline test cell mass flowrates. By scaling the costs to a uniform test cell mass flow of 660 lbm/sec, most of the cost differences were reconciled. Also, it was determined that the estimated cost for a wet-packed scrubber is 1.3 million fiscal year 1975 dollars. This cost does not include electric and other utility supply costs.

Available jet engine test cell information for the Alameda Naval Air Rework Facility was used to assess the impact of test cell operations on the environment. Impacts on source and air quality bases were considered. Since jet engine test cell emissions data are sparse, the more available and reliable jet engine exhaust data were used as the baseline uncontrolled jet engine test cell emissions. These emission levels are probably higher than test cell values and represent worst-case source conditions. Ground level pollutant concentrations outside the air base perimeter were obtained by an air quality model which incorporated worst-case meteorological data. These weather conditions maximize ground level pollutant concentrations and therefore represent worst-case air quality emission contributions.

On a source basis, worst-case Alameda jet engine test cell (JETC) operations contribute very little (less than 0.26 percent) to the total nine county Bay Area Air Pollution Control District (BAAPCD) emissions (unburned hydrocarbons, carbon monoxide, nitrogen oxides, sulfur oxides, particulates) inventory. Alameda JETC operations also represent less than 11 percent of the emissions produced by military aircraft operations in the BAAPCD region. Comparing worst-case Alameda JETC operations to base perimeter ambient background levels of pollutants on a 24-hour basis, it is estimated that JETC operations contribute, at most, 3 percent of particulates, 43 percent of unburned hydrocarbons, 0.3 percent of carbon monoxide, 6 percent of nitrogen oxides, and 34 percent of surfur oxides. Contributions to the background levels are much less than these maximum values at other locations.

Comparing worst-case individual Alameda JETC emissions with the BAAPCD General Combustion Source Regulations, it is calculated that 40 percent of Alameda JETC operations exceed the opacity regulations.

Applying wet-packed scrubber, clean combustor and ferrocene fuel additive control strategies to jet engine test cells reduces the impact of operations on ambient air quality in all respects except for NO_x. Clean combustors increase NO_x by approximately 50 percent. However, the increase is not large enough to alter the conclusion that JETCs contribute only minimally to the BAAPCD source inventory. Comparing controlled individual JETC emissions with General Combustion Source Regulations for the BAAPCD indicates that all control strategies will reduce the plume opacity below or near the stationary source opacity regulation. All control methods reduce particulate concentrations. Since uncontrolled concentrations are below regulations, controlled JETC particulate concentrations will be even further below the standards. Wet-packed scrubber and ferrocene fuel additive control strategies do not alter JETC gaseous emissions sufficiently to alter the conclusion that all gaseous emissions are below BAAPCD General Combustion Source Regulations. It is estimated that the T56 engine with clean combustors will produce NO_x emissions in excess of the regulation. If clean combustors were applied to the T56 engine, 9 percent of Alameda JETC operations would exceed the NO_x regulation.

Ferrocene added to the fuel is slightly toxic, but no more so than the fuel itself. When burned, ferrocene fuel additive yields primarily iron oxide, carbon dioxide, and water vapor. Taken alone, these substances are not very toxic; however, it has been suggested that synergistic reactions of iron oxide with combustion-produced polycyclic organic matter may produce carcinogens or transport them into the human body. Further study is required to prove or disprove this conjecture.

Controlled and uncontrolled JETC plume opacity, and gaseous and particulate emissions data collected during this study are briefly described. These data vary as a function of engine type, power level, and condition of the engine. Furthermore, the test cell itself affects emissions, according to the cell configuration, augmentor design and airflow, and quench water flow. Also, stack exit areas are typically large and test cell configurations generally create highly nonuniform distributions of stack exit velocity, which makes accurate measurement of emissions very difficult.

Published JETC stack-exist emissions data are very sparse. Also, they are limited since only a few (or one) sampling points are measured for a large stack exit area. In addition, isokinetic particulate sampling rates have not been maintained in some cases, casting doubt on the reliability of the particulate data.

In this report, the JETC emissions data collected during this study are briefly summarized. Comments on the reliability of the data and details of the (1) engine and test cell unit tested, (2) test method for opacity, particulates and gaseous emissions, (3) sampling locations, and (4) test cell conditions, as well as the data are presented.

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SECTION 1

INTRODUCTION

This report documents the results of the second phase of a two-phase program conducted by Acurex/Aerotherm to provide background information on jet engine test cell emissions and their controls to the Stationary Source Enforcement Division of the Environmental Protection Agency. This program was concerned primarily with military jet engine test cells in the United States.

As part of routine maintenance procedures, military jet aircraft engines are tested on stationary test stands or in test cells. The Navy, Air Force and Army all maintain facilities devoted to engine maintenance and testing. When tested, some jet engines produce a dark particulate plume which is often visible from a considerable distance, and recently, several military jet engine test cell facilities have been cited for violating local air pollution control district stationary source opacity regulations.

The military services are aware of these problems, and have established programs to characterize and control jet engine test cell emissions. Several military studies are currently underway to assess the effects of jet engine test cell emissions on ambient air quality.

Aerotherm's Phase I study on jet engine test cells, documented in EPA report EPA-340/1-78-001a (Reference 1), provided the following information:

- Physical descriptions of test cells and operating characteristics which alter jet engine exhaust emissions
- State-by-state location of military test cells
- Critical review of existing jet engine test cell data and measurement procedures for opacity, particulates and gaseous emissions
- Discussion of test cell emissions control by electrostatic precipitators, wet packed scrubbers, thermal convertors, improvements in fuel atomization and fuel additives

During the Phase 1 program, several areas of interest were identified which were beyond the scope of the initial effort. A Phase 2 program was then conducted to address these study areas. The results of the Phase 2 program, discussed in the following sections of this report, supplement the information in the Phase 1 report with:

- A survey of the state of the art of jet engine clean combustor technology and the associated cost and implementation time table of clean combustors by the military services
- An examination of wet packed scrubber cost estimates to determine the source of cost differential between Navy and private contractor estimates
- A brief summary of the environmental impact of controlled and uncontrolled jet engine test cells, including summaries of the impacts on a source and air quality basis
- A tabulation of available jet engine test cell emission data for both controlled and uncontrolled test cells

Currently, much activity is underway in all of these areas, and therefore, some information in this report is based on conversations with people in the field rather than on published results. The cooperation of military and government personnel in this regard is greatly appreciated.

The second section of this report discusses jet engine clean combustor technology and military schedules for implementing these combustors. The third and fourth sections discuss wet packed scrubber costs and the impact of controlled and uncontrolled jet engine test cells on the environment. The fifth section presents a tabulation of available jet engine test cell emissions data.

SECTION 2

CLEAN COMBUSTOR TECHNOLOGY

The January 1979 EPA emission standards for civilian aircraft jet engines (Reference 2) have stimulated an extensive development program by engine manufacturers and the government to produce advanced low-emission engines for the commercial jet fleet. Although military aircraft are exempt from compliance with the standard, the military services have actively moved to assess and reduce emissions levels from their jet engines.

As part of its effort to set emission goals for its jet aircraft, the Air Force's Aeropropulsion Laboratory has proposed gaseous emission goals to be applied to future military aircraft procurements (Reference 3). While lacking the force of legal limits, these goals provide substantial encouragement for manufacturers to incorporate emission reductions on military engines. For engine smoke emissions, the Air Force has promulgated a smoke number goal for new procurements (Reference 4).

This section discusses how clean combustor technology is applied by the military to reduce smoke, particulates and gaseous emissions from aircraft jet engines. Because of large efforts to meet the mandated EPA standards, the civilian emissions reduction program leads the military program. Therefore, the following discussion on clean combustor technology will use information generated for civilian aircraft applications. Because military and civilian engine performance and durability goals are different,

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extrapolation of civilian technology to military engines is not straightforward. However, it is anticipated that much of the civilian technology will be applicable to military jet engines.

In the following two subsections, current aircraft engine emission characteristics and civilian clean combustor technology programs are discussed. These subsections are followed by a description of military clean combustor programs, including Air Force and Navy clean combustor retrofit program schedules and costs. In addition, the impact of new procurements of clean combustor engines on military aircraft emissions will be discussed.

2.1 CURRENT CIVILIAN AIRCRAFT ENGINE EMISSIONS

The January 1979 EPA standards for civilian aircraft jet engines represent what the government believes is an achievable emissions goal. These standards are used as a point of reference to determine how near civilian aircraft jet engines come to meeting the standards, what current combustor technology tests can achieve, and how far combustor technology must be advanced to fully meet the standards.

The January 1979 EPA standards for civilian aircraft jet engines given in Reference 2 are shown on the following page. Gaseous emission characteristics are described by the EPA parameter (EPAP). The EPAP is a measure of the total emissions of a particular pollutant produced by an engine over a typical landing-takeoff (LTO) cycle normalized with respect to the total impulse (for jet thrust engines) or total energy (for turboshaft or turboprop engines) produced over that cycle. The EPA exhaust smoke limitation is a specified smoke number.* This smoke number is a relative measure of exhaust visibility and may or may not be directly related to the concentrations of particulate emissions. Currently, no limitation is set to control the particulate emissions from aircraft engines.

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*A smoke number is obtained by filtering a known quantity of the stream through a filter paper and measuring the reflectance of the soiled filter paper.

	THC EPAP[a]	CO EPAP	NO_x EPAP	Nominal EPA Smoke Number Required
Class T1 (Thrust level <8000 lb_f)	1.6	9.4	3.7	30
Class T2[b] (Thrust level >8000 lb_f)	0.8	4.3	3.0	20

THC -- Total unburned hydrocarbons
CO -- Carbon monoxide
NO_x -- Oxides of nitrogen

[a] EPAP parameter units are lbm pollutants/1000 lbf thrust-hours/cycle.

[b] Classes higher than T2 have standards identical to the T2 class.

As can be seen in the above table, the smoke standards vary depending on engine size. Reference 2 compares smoke and gaseous emission characteristics of current civilian aircraft engines to the January 1979, EPA standards. From this comparison, it can be concluded that almost all of the current civilian aircraft engines meet the 1979 EPA smoke standards, but that none of the engines meet the gaseous emission standards.

2.2 CLEAN COMBUSTOR TECHNOLOGY

Civilian programs to develop clean combustor technology were initiated in the mid-sixties to reduce exhaust smoke, an obviously undesirable emission visible to the public. During 1970, the potential degradation of air quality due to the gaseous emissions from jet engines became a public concern, and in 1972, standards to control the gaseous emissions from civilian aircraft were promulgated by the EPA. These standards prompted the development of new technology to control both gaseous and smoke emissions from jet engines.

This section describes the current status of civilian engine clean combustor technology. The emission characteristics of jet engines are briefly discussed to provide some background information on how design parameters and engine operation modes affect emission levels. Following this, a brief survey of combustor concepts with the potential to reduce emissions are presented. Finally, the effectiveness of these emission control concepts in reducing combustor emissions from current production civilian engines is described.

2.2.1 Pollutant Emission Characteristics of Jet Engines

The emission characteristics of a typical civilian or military non-afterburning engine are illustrated in Figure 1. As can be seen, the greatest concentrations of pollutants are formed at the two extremes of the engine operating power range: low-power idle and high-power takeoff. At idle, CO and THC are the principal pollutants, while at takeoff, NO_x and smoke reach maximum levels.

The high levels of CO and hydrocarbons at idle are attributable to the poor combustion conditions encountered. Problems with flame quenching, fuel/air distribution, fuel atomization, and combustion intensity* work to make combustion at idle inefficient and incomplete. At high power takeoff, combustion efficiency is nearly 100 percent and only small amounts of CO and THC are produced. However, the higher temperature and pressure levels within the combustor lead to the generation of NO_x. The cause of a high smoke

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*Intense combustion occurs when there is rapid turbulent mixing of fuel and air as well as vaporization and burning of fuel droplets.

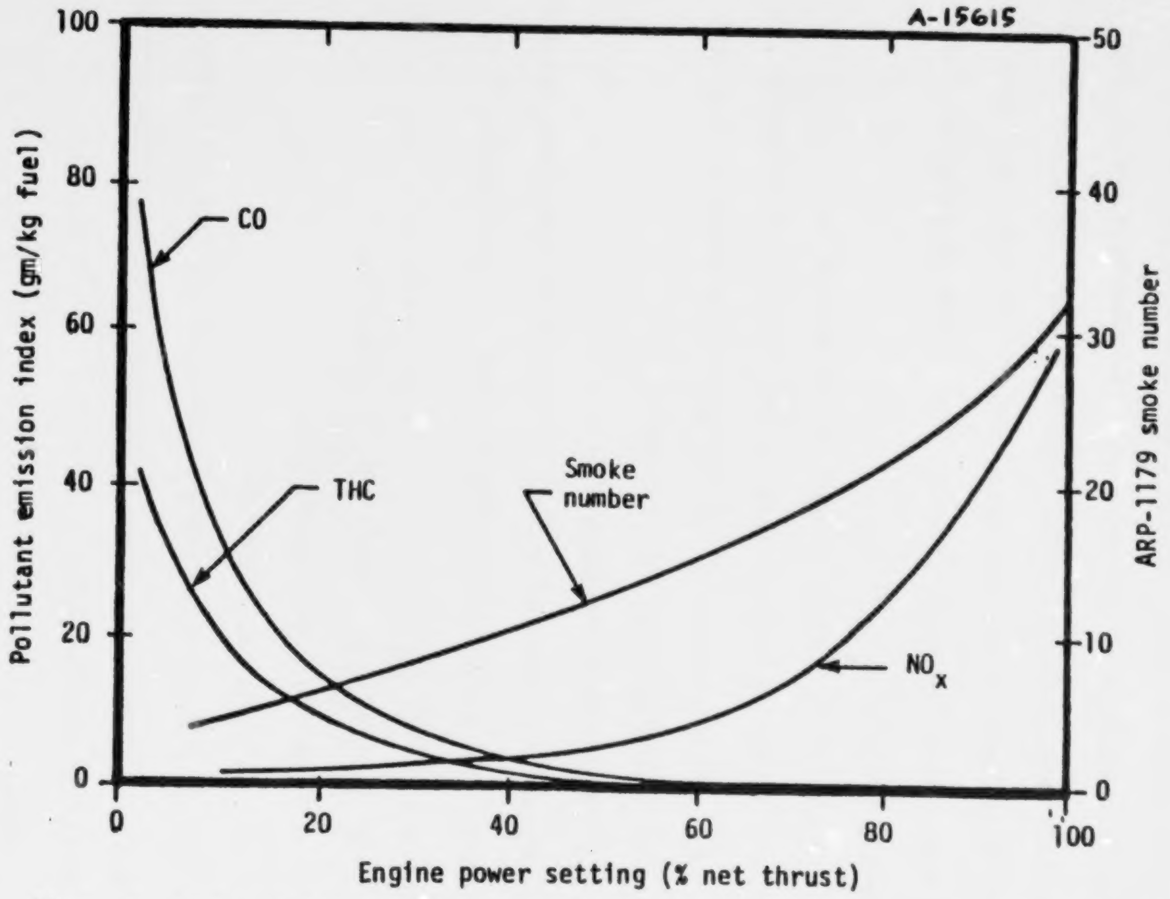

Figure 1. Typical nonafterburning turbine engine emission trends (Reference 3).

number at takeoff is primarily the high pressure level within the combustor. This enhances the formation of soot particles. Because these particles -- generally 1 micron in diameter or less -- are highly visible, the opacity of the exhaust plume is high. At low power settings, particulates can also occur by condensation of hydrocarbons. The condensed hydrocarbons tend to agglomerate into particles larger than 10 microns (Reference 5), which are less visible than those in the submicron range. Therefore, low smoke numbers are often measured at low power settings even though particulate concentrations may be significant.

CO and THC emissions at idle can be reduced by:

- Improving fuel atomization and fuel/air distribution
- Increasing overall equivalence ratio (ratio of fuel/air ratio to stoichiometric fuel/air ratio)
- Increasing residence time

These changes will have the effect of increasing combustion intensity and uniformity, and allowing more time for fuel to react before it is cooled by secondary airflow.

NO_x emissions at takeoff can be reduced by:

- Lowering flame temperature
- Reducing residence time

Since NO_x generation is a strong function of the time the combustion products are at high temperature, reducing temperature and residence time will lower NO_x emissions considerably.

Smoke emissions can be reduced by:

- Improving fuel atomization and thereby fuel/air distribution
- Leaning out the local fuel-rich areas in the primary combustion zone by improved fuel/air distribution

- Increasing residence time

Decreasing the number of rich zones will decrease the formation of soot nuclei, and increasing the residence time will allow more of the soot to be burned up.

It is apparent from the brief discussion above that design changes made to reduce an emission at one operating condition could increase the level of a different emission at another operating condition. Therefore, reducing all emissions at all operating conditions is not a straightforward task. Much work must go into the design of a new engine to achieve low emission levels for all pollutants at once. Because of additional design constraints, it is even more difficult to achieve low emission levels by modifying an existing engine.

Very little information is presently available on pollutant emissions from afterburning engines. However, general trends from some data on afterburning engines (References 6 through 10) indicate possible significant emissions of CO and THC, especially at the lower afterburner power settings. Limited data also show that the amount of NO_x produced in afterburners is small due to relatively low pressures, small residence time and low flame temperatures (Reference 11). Smoke emission levels during afterburner operation are found to be low because of low pressure levels and slightly lean local fuel/air mixtures. In fact, tests have shown that particulates generated from the upstream main combustor were partially consumed in the afterburner due to increased soot residence time at high temperature (Reference 11).

2.2.2 Overview of Current Low Emissions Technology

Considerable testing of low emissions combustor concepts has been conducted by manufacturers to develop clean engines that meet the 1979 EPA standards. These efforts have mainly focused on fuel preparation techniques, especially in nozzle design. A summary and very brief discussion of the concepts tested, extracted from Reference 12, is presented in Table 1. So far, no single technique tested has been effective in simultaneously reducing NO_x, THC, and CO to the levels required by the 1979 EPA standards over the entire operating range of an engine. Some of the concepts tested did, however, demonstrate potential to meet the 1979 standards for a given pollutant.

Some of the listed concepts can also reduce smoke levels, although they are designed primarily for reducing gaseous emissions. As described previously, smoke reduction can be achieved by improved atomization and fuel/air distribution, which eliminates local fuel-rich regions in the primary combustion zone. Hence, concepts listed in Table 1 that improve one or both of these processes can be used to reduce smoke emissions.

The lean primary zone, water injection and rich primary concepts tested can increase smoke emissions. In the first two concepts, a large quantity of air or water is introduced into the combustion chamber to lower the flame temperature and to reduce the rate of NO_x formation. However, reducing the flame temperature also causes combustion instability, resulting in flame quenching and the formation of particulates. The rich primary concept was designed to reduce CO and THC emissions by operating the reaction zone under a richer condition than the normal fuel/air ratio. The high flame temperature enhances the conversion of CO to CO_2 and the oxidation of hydrocarbons. However, the higher flame temperature also enhances NO_x formation, and if the equivalence ratio is greater than one, particulates may also start to form.

TABLE 1. SUMMARY OF LOW EMISSION CONBUSTOR CONCEPTS

Category	Concept	Approach	Impact on Operations		Effects on Pollutant Emissions				Effort Required to Implement
			Idle	High Power	CO	UHC	NO_x	Particulate Smoke	
Fuel Preparation	Airblast	Engine pressure differential used to achieve high velocity air jet which is directed towards fuel injectors. This helps break up fuel droplets and eliminate locally-rich hot spots.	Small	High	Reduction	Reduction	Uncertain	Reduction	Minor
	Air Assist	Same as above, except to maintain airblast at low power operation auxiliary air compressors must be installed.	High	High	Reduction	Reduction	Uncertain	Reduction	Major (Need auxiliary compressor)
	Premix	Fuel and air are mixed in a prechamber prior to entering primary combustion zone. Premixing allows stable combustion at a leaner primary zone fuel/air ratio, thereby reducing NO_x formation.	Some	High	Reduction	Reduction	Reduction	Reduction	Major (Longer combustor)
	Fuel Atomization	Pressure differential and fuel nozzle geometry changes to reduce droplet sizes, increasing CO and UHC burnup. However, hotter mixture will increase NO_x.	Some	High	Reduction	Reduction	Increase	Reduction	Minor
Fuel Distribution	Fuel Staging	Combustor divided into pilot and main stages. At low power only pilot stage is used with an optimum fuel/air ratio to reduce CO and UHC. At high power, staging is optimized to reduce NO_x.	High	High	Reduction	Reduction	Reduction	Reduction	Major (Two sets of fuel nozzles, etc.)

TABLE 1. Continued

Category	Concept	Approach	Impact on Operations		Effects on Pollutant Emissions				Effort Required to Implement
			Idle	High Power	CO	UHC	NO_x	Particulate Smoke	
Fuel Distribution (Continued)	Nozzle Design	Modify fuel nozzle to reduce wetting of combustor wall and thus UHC, while maintaining adequate fuel/air distribution.	High	High	Reduction	Reduction	Same	Reduction	Minor
	Fuel Sectoring	Fuel injected selectively at various power levels to optimize fuel/air distribution for both idle and high power.	High	Small	Reduction	Reduction	Same	Reduction	Minor
Air Distribution	Lean Primary	A larger percentage of combustor airflow is introduced into the primary reaction zone creating a leaner mixture which prevents NO_x. However, quenching and CO emissions are increased.	Some	High	Increase	Increase	**Reduction**	Increase	Minor
	Rich Primary	A smaller percentage of combustor airflow is introduced into the primary reaction zone creating a richer mixture which promotes the conversion of CO to CO_2 and the consumption of UHC. However, primary zone is hotter, which results in increased NO_x.	Some	High	**Reduction**	**Reduction**	Increase	Increase	Minor
	Delayed Dilution	By delaying secondary zone dilution air, a longer combustion zone at moderate temperatures is produced. This should result in increased CO and HC burnup with only marginal increase in NO_x.	Some	Some	**Reduction**	**Reduction**	Increase	**Reduction**	Minor

TABLE 1. Concluded

Category	Concept	Approach	Impact on Operations		Effects on Pollutant Emissions				Effort Required to Implement
			Idle	High Power	CO	UHC	NO_x	Particulate Smoke	
Air Distribution (Continued)	Variable Geometry	Airflow to primary and secondary reaction zones controlled by mechanical means to optimize fuel/air distribution at both idle and high power.	High	High	Reduction	Reduction	Reduction	Reduction	Major (Mechanical control of airflow over full operating range)
Improvements in Combustor Operating Conditions	Idle Speed Increase	By increasing idle speed, engine operates in intermediate power regime where NO_x is still low and CO and UHC are much reduced. Fuel consumption increases.	High	None	Reduction	Reduction	Increase	Reduction	Minor
	Airbleed	Increased idle speed with engine power dissipated in compressor by airbleed. Same effect as above concept.	High	None	Reduction	Reduction	Increase	Reduction	Minor
	Increased Combustor Length	Increased combustor length allows more burnup time for CO and UHC. However, larger residence times tend to increase NO_x.	Some	Some	Reduction	Reduction	Increase	Reduction	Major (Longer engine, major redesign)
	Water Injection	Injection of water reduces primary zone temperature and hence NO_x. Too much water increases CO.	Some	High	Increase	Increase	Reduction	Increase	Major (Water supply, deposits on engine problem)

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2.2.3 Application of Concepts to Current Civilian Production Engines

As reported in Reference 12, some of the combustor concepts listed in Table 1 were applied to civilian aircraft engine combustors. Experimental combustor tests were performed to evaluate the effectiveness of each concept in reducing gaseous as well as smoke emissions. The emission performance of the best demonstrated combustor concepts were determined. These test results were adjusted to reflect the emission characteristics of an entire engine in its various operating modes. Comparing the adjusted combustor results to the 1979 EPA standards indicates that the NO_x standard was achieved (without water injection) by only 33 percent of the engines listed, while the CO and THC standards were achieved by 54 percent and 75 percent of the engines, respectively. Although the smoke emission data indicated smoke levels were below the EPA smoke standards, none of the engines met all of the 1979 EPA gaseous emissions standards. From these results, it can be concluded that more than one concept will probably have to be applied to reduce all pollutants to levels below the 1979 EPA standards.

In addition to the technology development described above, the National Aeronautics and Space Administration (NASA) has also sponsored programs to develop clean combustors for current commercial aircraft engines. Their goal was to modify existing engines to meet the 1979 EPA standards without sacrificing engine performance. The jet engines selected for redesign included:

- CF6-50
- JT9D-7
- JT8D-17

- TFE731-2
- 501-D22A

The NASA programs are being conducted in three phases: Phase 1 consisted of experimental screening tests of low-pollution combustor concepts; Phase 2 consisted of experimental test rig refinement of the most promising combustor concepts; and Phase 3, currently in progress, consists of incorporating and evaluating the best combustors as part of a complete engine. Detailed information on the NASA programs can be obtained from References 13 to 20.

Based on the Phase 2 experimental combustor rig test results, an optimal low-pollution combustor concept was selected for each engine as follows:

- Double annular concept -- CF6-50 engine
- Vorbix concept -- JT9D-7 engine
- Vorbix concept -- JT8D-17 engine
- Piloted-airblast concept -- TFE731-2 engine
- Reverse flow concept -- 501-D22A engine

All of these concepts, except piloted airblast, used both fuel and air distribution techniques (see Table 1); for piloted airblast, only fuel preparation techniques were used.

The experimental results with these concepts were extrapolated to actual engine conditions and compared with the 1979 EPA standards. As shown in Table 2, advanced technology combustors have reduced aircraft engine emissions significantly, although actual compliance with 1979 EPA standards was achieved in only one case (501-D22A). Smoke emissions have increased somewhat, but are still at the low levels characteristic of the baseline engines.

TABLE 2. SUMMARY OF EMISSION LEVELS (EPAP VALUES) ACHIEVED WITH THE "SELECTED" ADVANCED TECHNOLOGY COMBUSTOR CONCEPTS (Reference 13)

Emissions / Engines	CO			THC			NO_x		
	Conv Comb	Adv Tech	EPA Stds	Conv Comb	Adv Tech	EPA Stds	Conv Comb	Adv Tech	EPA Stds
CF6-50 Engine (Double Annular Concept)	10.8	3.0	4.3	4.3	0.3	0.8	7.7	4.2	3.0
JT9D-7 Engine (Vorbix Concept)	14.3	6.3[a]	4.3	5.3	0.6	0.8	4.9	3.5	3.0
JT8D-17 Engine (Vorbix Concept)	16.1	9.0[a]	4.3	4.4	0.2	0.8	8.2	4.3	3.0
TFE731-2 Engine (Piloted-Airblast Concept)	17.5	10.1	9.4	5.3	0.4	1.6	5.3	3.9[b]	3.7
501-D22A Engine (Reverse Flow Concept)	31.5	4.6	26.8	15.0	0.3	4.9	6.2	7.3	12.9

Smoke requirements should be achievable for all concepts

[a] Lower values expected with further developments

[b] Preliminary value

Efforts to date indicate that applying these concepts to actual engines will not increase smoke levels.

In summary, smoke reduction technology for civilian aircraft engines is well defined. To reduce gaseous emissions below the 1979 EPA standards, major combustor redesign, incorporating one or more of the above concepts, will be required. In combustor rig tests, NASA has demonstrated clean combustor technology which comes close to meeting the standards for five commercial aircraft engines. However, NO_x emissions still remain a problem.

Because civilian jet engine clean combustor programs have been successful in reducing gaseous emissions while maintaining low smoke levels, and because civilian and military jet engines are fundamentally similar, most military jet engines probably can be made clean. However, applying these civilian engine concepts to military engines is difficult because of the more rigid military engine performance and durability constraints. This difficulty is multiplied when an existing engine is modified to reduce emissions. The success to date with attempts to apply clean combustor techniques to existing military engines is mixed; many engines have responded well, while some -- for reasons not fully understood -- have not been successfully retrofitted. Also, some military engines have afterburners, and none of the civilian combustor concepts apply to the afterburners of military jet engines.

2.3 MILITARY CLEAN COMBUSTOR PROGRAMS

Military interest in reducing smoke from jet engines goes beyond environmental considerations. Because visible smoke emissions can make military aircraft easy to track in the sky and increase their vulnerability, low-smoke combustor development programs were initiated by the military in 1965 (Reference 11). At the same time, smoke emissions from civilian aircraft became a concern of the public, since these emissions were visible air pollution. The combined efforts of both military and civilian organizations have developed the technology needed to design new jet engines which have virtually invisible exhausts, yet adequate engine ignition and performance characteristics.

In the following sections some low-smoke combustor concepts applied to military engines are discussed. These concepts are similar to those applied to civilian engines to reduce gaseous emissions while maintaining low smoke levels. Next, a short compilation of smokeless engines and their percent of total current Air Force and Navy inventory is given, followed by the future engine emissions goals of the military. Finally, the military programs currently underway to clean up engine emissions are described, along with their associated costs.

2.3.1 Low-Smoke Military Jet Engines

Military low-smoke combustors employ techniques which are, in principle, the same as those applied in civilian engines. The combustor is redesigned to:

- Lean-out local fuel-rich regions in the primary combustion zone
- Improve fuel atomization and fuel/air distribution

These characteristics are achieved in practice by admitting the airflow into the primary combustion zone with a strong swirl for enhanced mixing and modifying the fuel nozzle pattern and shroud airflow to improve fuel atomization. The more uniform fuel/air mixture created by these changes permits a slight leaning-out of the primary zone mixture ratio. The impact of these changes on engine smoke emissions is a strong function of combustor type; some combustors respond more easily to these changes than others. For the changes to be effective, it is essential that they be carefully tailored to the engine design. Also, it is much easier and more effective to incorporate these changes into a new design than to modify an existing engine.

The success of low-smoke combustor design changes is illustrated in Figure 2, a comparison of the exhaust opacity of several older, smoky engines with new smokeless combustor military jet engines. Table 3 also compares other smoky and smokeless military jet engines which are different models of the same basic engine. Smoke levels for most of the smokeless engines are reduced below the threshold of visibility.

TABLE 3. SMOKELESS MILITARY ENGINES

Engine[a]	Manufacturer	SAE Smoke Number Smokeless	Smoky	References
TF30	Pratt & Whitney	15	78	21
J52	Pratt & Whitney	30	63	21
J65	Curtiss-Wright Corp.	11	--	21
F100	Pratt & Whitney	36	--	3
TF34	General Electric	12	--	3

[a] The smoky and smokeless engines are different models of the same basic engine.

General Electric's advanced annular combustor design is an example of current low-smoke combustor technology. In this design, large amounts of the combustor airflow are introduced through swirl cups containing axial flow swirlers which surround each of the fuel nozzles. With this approach, lean and relatively uniform primary zone fuel/air mixtures are obtained as a result of the rapid and effective fuel/air mixing produced by the air swirlers. Smoke levels are much reduced without significant

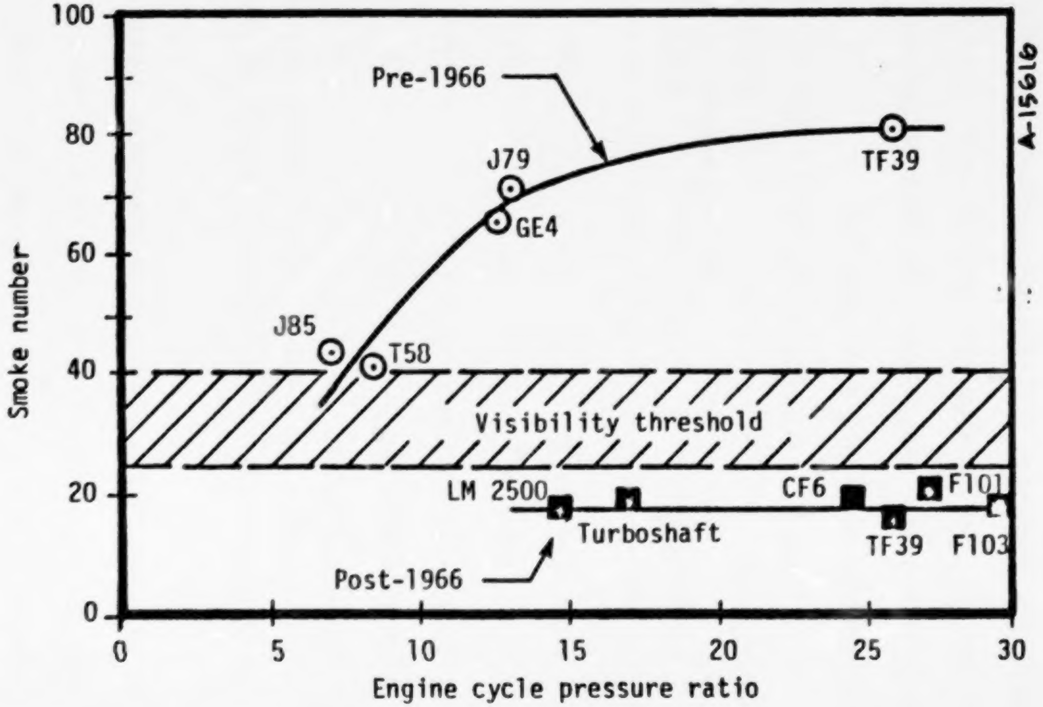

Figure 2. Peak smoke levels — General Electric (GE) engines (Reference 11).

losses in ground ignition, altitude relight performance, or other combustor performance characteristics. This design approach has been successfully applied to the entire General Electric TF39 family of engines: TF39, LM2500, and CF6. Note that the TF39 engine does not incorporate afterburners and the CF6 is a commercial aircraft engine. The advanced TF39 smoke emission levels are shown in Figure 3.

Significant smoke reductions can also be obtained from older engine designs by retrofitting advanced clean combustors. The J79 engine previously had a smoke number of 60 to 70 with kerosene fuel. A modified combustor design was developed which renders its peak smoke level virtually invisible at a smoke number of approximately 30. This reduction is achieved by incorporating changes in the combustor's dome, liner and fuel nozzle to improve combustion through better fuel/air mixing and the elimination of fuel-rich areas. Many trial-and-error design changes had to be made to this engine before an acceptable design was found. Figure 4 shows the smoke emission levels of the improved J79 engines.

Incorporating this retrofit design approach into J79 engines is expensive. According to an estimate by the Air Force, it is believed that over $30,000 per engine in current dollars will be required to retrofit the J79 engine with a smoke-reduction combustor (Reference 22). The Navy is in the process of retrofitting 900 J79 engines at an estimated cost of $40,000 per engine in current dollars (Reference 23).

Other types of low-smoke emission combustor approaches for advanced engines like the F101, TF34, and T700 also were developed at General Electric. In these approaches, the fuel is injected at low pressure and is airblast-atomized by part of the combustor airflow as it is delivered into the primary combustion zone. Because of the very effective fuel atomization

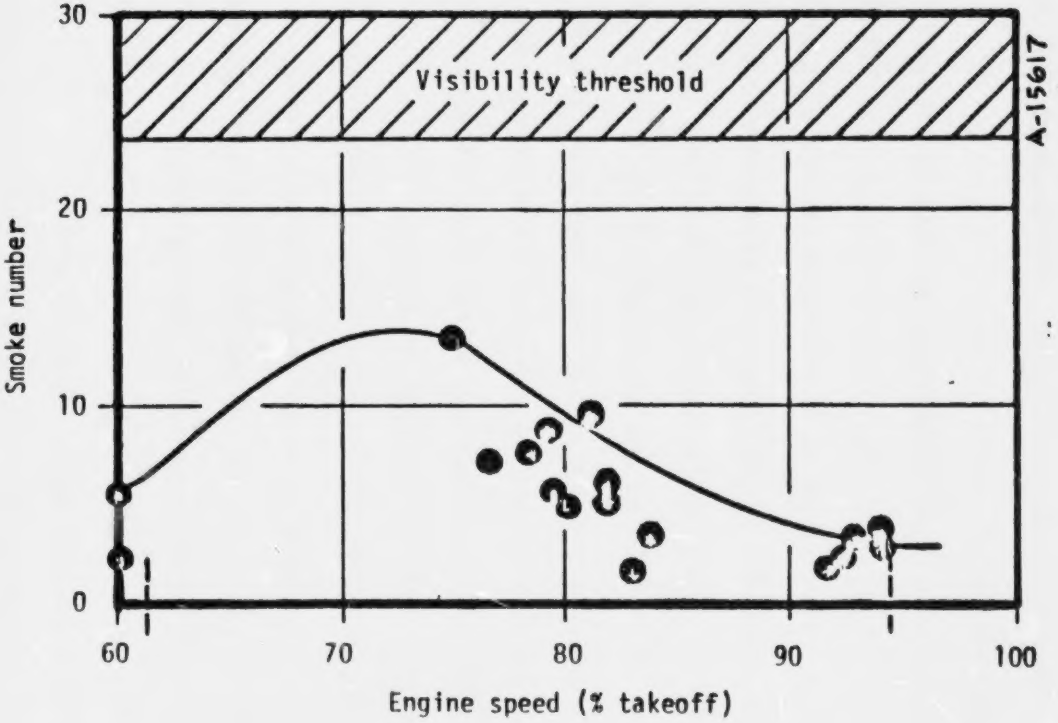

Figure 3. Smoke emission characteristics of TF39 engine using the axial swirler combustor (Reference 11).

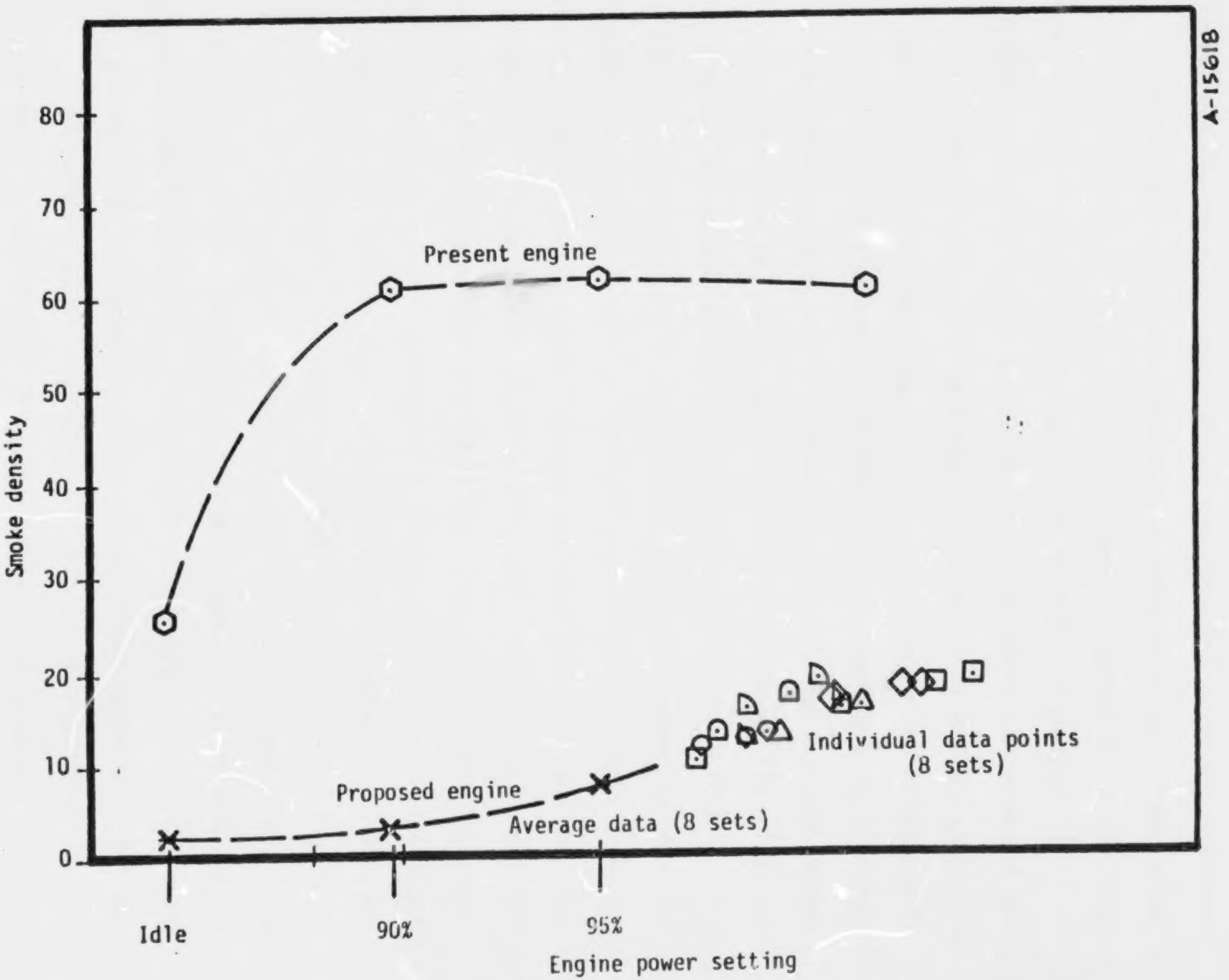

Figure 4. J79 engine smoke levels (Reference 22).

and fuel/air mixing attained with these airblast atomization techniques, combustor designs of this kind were found to have low smoke emission levels. As an example, the smoke emission characteristics of the F101 engine combustor are presented in Figure 5.

By applying this type of smoke reduction technology in retrofit and new procurement programs, a significant portion of current military engine inventory has been made smokeless. According to Air Force and Navy personnel, 28 percent of Air Force engines and 40 percent of Navy engines currently are smokeless. This achievement, coupled with the fact that most current civilian jet engines are smokeless, is encouraging evidence that eventually all non-afterburning military engines will be made smokeless.

Actual measurements of particulate concentrations at jet engine exits for smoky and smokeless versions of the same engines are sparse. Typically, smokeless combustor modifications are combined with performance improvement modifications to produce an engine that has different emissions and performance than the original engine. This makes a direct comparison of smoky/smokeless combustor emissions difficult. One data source (Reference 24) indicates that particulate concentrations, as well as smoke levels, are reduced by smokeless combustors. In Reference 24, a J52 engine redesigned with new smokeless combustors had particulate concentrations which were 25 percent lower than the original engine. However, it was noted that the smokeless version of the J52 was substantially changed from the original smoky engine. Use of known smoky and smokeless engine smoke numbers and a correlation of particulate concentration versus smoke number (see the environmental impact summary section) indicates that smokeless combustors can reduce particulate concentrations by 94 to 98 percent. However, the correlation is not precise and may not be valid for comparing smoky and smokeless engines. Based on the

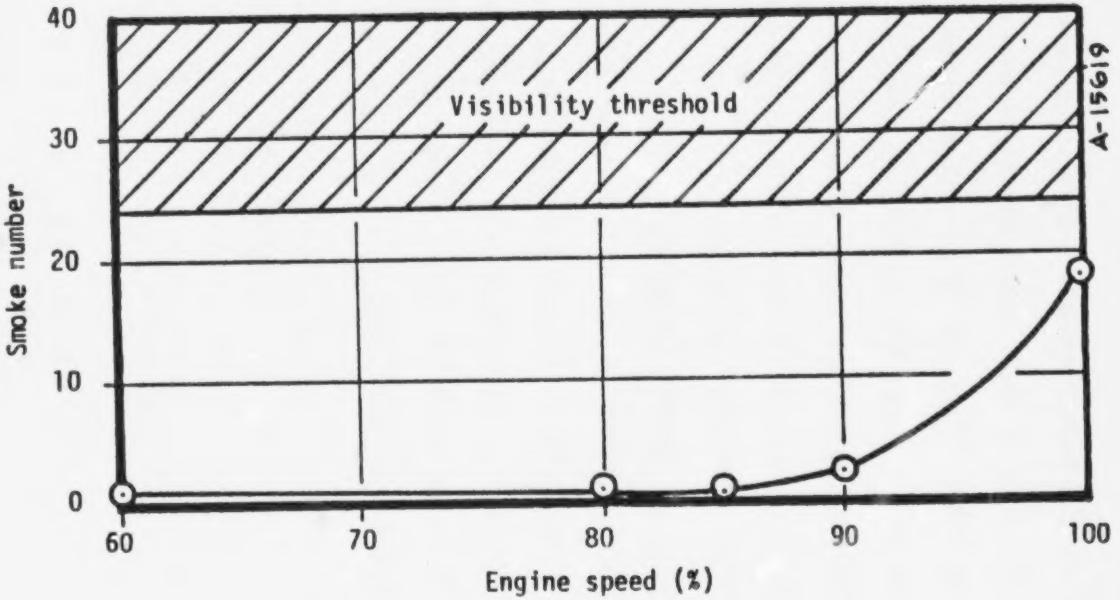

Figure 5. Smoke characteristics of advanced F101-type premixed combustor (Reference 11).

above limited information, it is estimated that particulate concentration for smokeless combustor engines are reduced 25 percent below the baseline smoky engine values.

The impact of low-smoke combustors on gaseous emissions was assessed, based on the limited data on smoky versus smokeless engines given in Table 4. As shown by the table, there was no consistent pattern of peak THC and CO emissions variation when low smoke combustors were applied to these four engines. All smokeless engines had higher NO_x emissions than the conventional engines. Based on this data, an increase of roughly 50 percent in NO_x is estimated if smokeless combustors are used.

2.3.2 Military Goals for Gaseous Emissions

Goals to control gaseous emissions from nonafterburning military engines have been established by the Air Force Aeropropulsion Laboratory (AFAPL). Like EPA standards, these emissions goals are divided into two levels: one for 1979, the other for 1981. These goals (described in Reference 3) are summarized as follows:

	1979 Goals	1981 Goals
Combustion Efficiency at Idle	99 percent for idle pressure ratio $> 3:1$[a]	99 percent for idle pressure ratio $> 3:1$
	98 percent for idle pressure ratio $\leq 3:1$	98 percent for idle pressure ratio $\leq 3:1$
NO_x % Reduction from Uncontrolled Level	25 percent without water injection	50 percent without water injection
	75 percent with water injection	

[a] Combustor pressure to ambient pressure at idle

TABLE 4. COMPARISON OF SMOKY AND SMOKELESS JET ENGINE GASEOUS EMISSIONS

	Smoky				Smokeless				Reference
	THC	CO	NO_x	Smoke	THC	CO	NO_x	Smoke	
JT3D[b]	34.2 (EPAP)[a]	40.8 (EPAP)	3.8 (EPAP)	53 (SN)[a]	18 (EPAP)	26.2 (EPAP)	5.6 (EPAP)	16 (SN)	12
JT8D[b] (Peak Values)	378 (PPM)[a]	744 (PPM)	70.4 (PPM)	28 (SN)	200 (PPM)	590 (PPM)	70 (PPM)	60 (SN)	25
	350 (PPM)	420 (PPM)	110 (PPM)	80 (SN)	220 (PPM)	350 (PPM)	180 (PPM)	33 (SN)	26
J79-GE15 (Peak Values)	9 (lb/k lb fuel)[c]	25.8 (lb/k lb fuel)	9 (lb/k lb fuel)	65 (SN)	40 (lb/k lb fuel)	30 (lb/k lb fuel)	18 (lb/k lb fuel)	25 (SN)	22
TF39 (Peak Values)	15 (lb/k lb fuel)	50 (lb/k lb fuel)	38 (lb/k lb fuel)	80 (SN)	15 (lb/k lb fuel)	50 (lb/k lb fuel)	40 (lb/k lb fuel)	5 (SN)	27

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[a] EPAP -- Parameter units are lbm pollutant/1000 lbf thrust-hours/cycle
PPM -- Parts per million
SN -- Smoke number

[b] The JT3D and JT8D are commerical jet aircraft engines, which have some design similarities with the J57 and J52 military engines respectively.

[c] Abbreviation for pounds/thousand pounds of fuel

Figures 6 and 7 show the emissions goals as they relate to the current emission levels of military engines. One important provision of these goals is that any emissions control design feature must not infringe upon the engine design and operation to compromise engine effectiveness. These emissions goals are still being examined by the Office of Secretary of Defense at the present time, and have not yet been promulgated (Reference 28).

To meet military emissions goals for non-afterburning engines, military engines (like civilian engines) will require significantly more advanced combustors. These combustors will be produced in military-funded programs that will make maximum use of available advanced combustor technology for civilian engines (References 22 and 29).

Military engines such as the TF39, J52, and T56, are similar in design to the CF6, JT8D, and 501 civilian aircraft engines upon which NASA-sponsored advanced gaseous emission control technology has been experimentally demonstrated. It is anticipated that if the NASA clean combustor technology were applied to these engines, the gaseous emissions levels would fall below or near the military emission goals. However, engine performance or durability might degrade if these changes are directly applied. Only an extensive design and test effort will demonstrate conclusively whether civilian jet engine clean combustor technology can be applied to non-afterburning military jet engines.

Furthermore, to reduce NO_x emissions from nonafterburning engines to levels comparable to the 1979 EPA standard requires an advance in control technology beyond that currently available from the civilian sector.

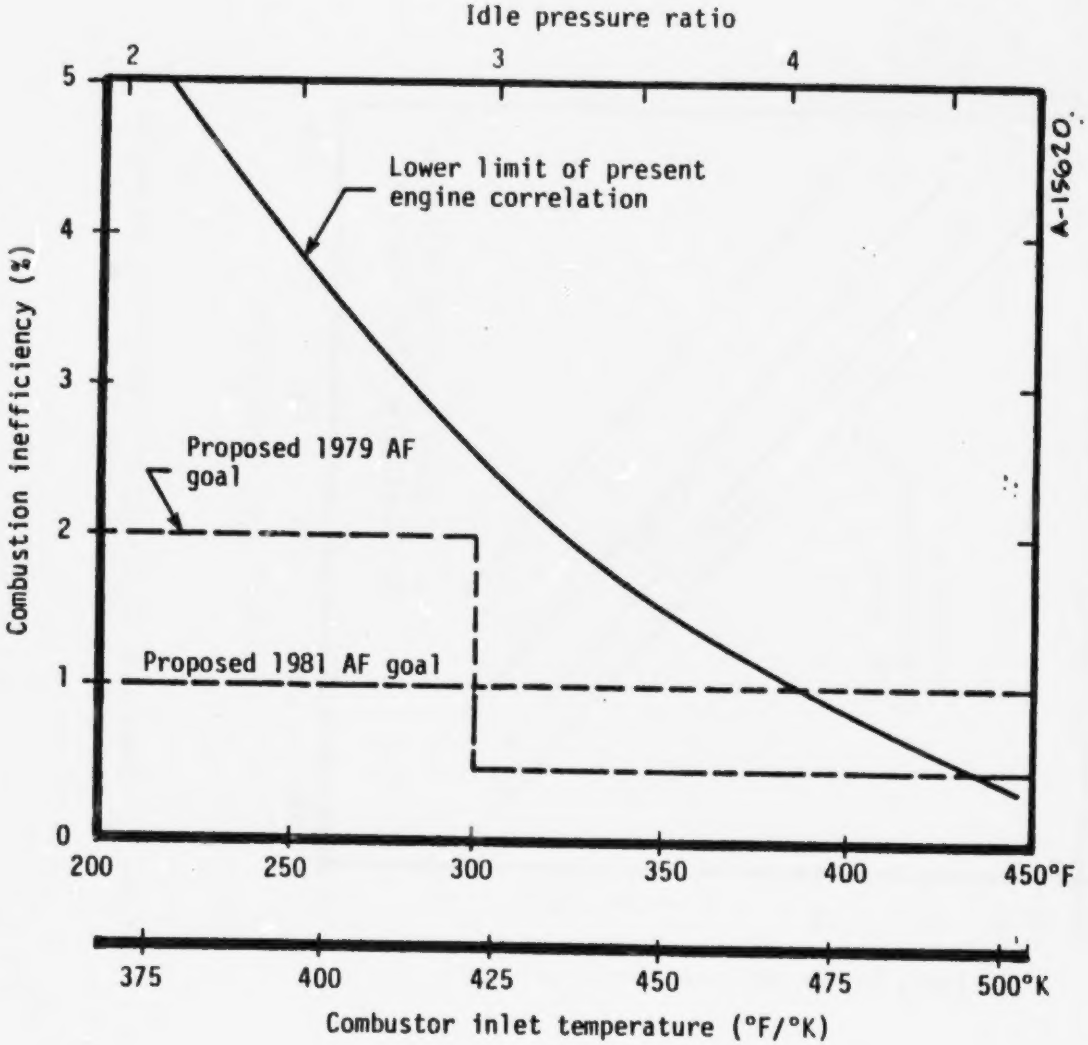

Figure 6. Comparison of current and future jet engine efficiency goals (Reference 3).

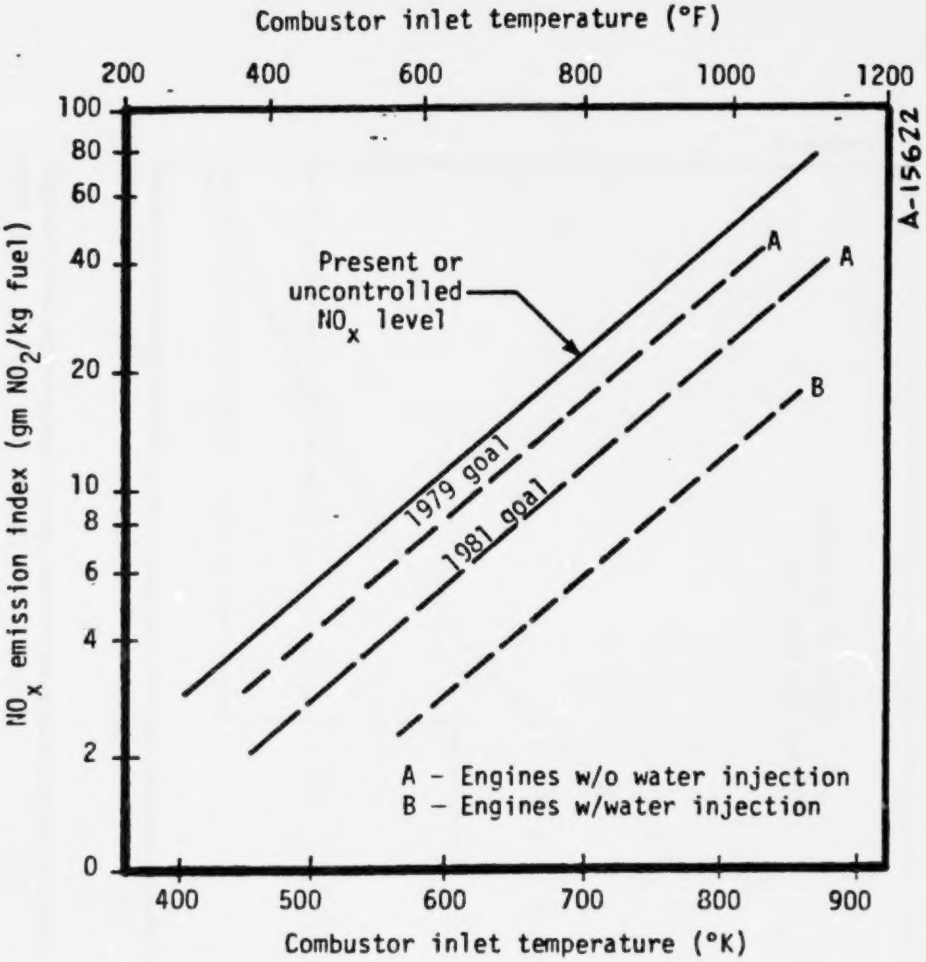

Figure 7. Comparison of current and future NO_x jet engine emission goals (Reference 3).

2.3.3 Implementation of Low-Smoke Combustor Programs by the Military

Table 5 shows the current percentages of low-smoke engines in the Air Force and the Navy engine inventories, as well as the projected numbers for the future (References 29 and 30). The percentage of low smoke engines will increase by:

- Retrofitting some old engines with low-smoke combustors -- total anticipated is on the order of thousands
- Procuring new low-smoke engines -- on the order of several hundred per year
- Retiring older smoky engines

TABLE 5. PERCENT OF LOW-SMOKE ENGINES IN THE MILITARY ENGINE INVENTORY

	Percent of Low Smoke Engines	
	Air Force	Navy
Current status	28	40
Future Projection	40 (1984)	65 (1985)

The Air Force currently has a program to retrofit both TF39 (C5 aircraft) and a small number of F100 engines (F15 and F16 aircraft) with low-smoke combustors (Reference 30). The TF39 program, recently completed in cooperation with General Electric, included retrofitting 343 in-service engines and procuring 123 production engines at an estimated smoke reduction cost of $1,659,101 and $1,236,060, respectively, in current-year dollars. In addition to lowering smoke emissions, the new combustors have also extended the overhaul time from 1000 service hours to 3000 service hours (Reference 31).

The F100 program, in cooperation with Pratt and Whitney Aircraft Corporation, is just beginning and no detailed cost information has been obtained. Also, the program is based on routine overhauls and no definite program completion date can be forecast at this time (Reference 30).

As reported in 1974 (Reference 3), the Air Force has considered retrofitting other engines. Table 6 lists these engines, along with an estimated implementation cost. It was estimated that retrofit of the engines listed would cost approximately $265 million (Reference 3). Of course, this 1974 estimate of total cost as well as the individual costs would be much higher in terms of current dollars as a result of inflation and other cost escalators.

The older, smoky engines will be phased out according to standard retirement schedules.

TABLE 6. SMOKE RETROFIT COST SUMMARY FOR AIR FORCE ENGINES (REFERENCE 3)

Engine	Inventory	Year Introduced into Inventory	Total Cost[a] ($ Million)
J57	10,475	1956	115
J79	4,709	1961	48
T56	3,533	1958	45
TF30	2,672	1965	37
TF33	1,831	1961	20

Total Projected Retrofit Cost: $265 million

[a] Costs estimated in 1974

In 1972 the Navy tentatively scheduled six engines for retrofit with low smoke combustors (Reference 21). The retrofit schedule for these engines is given in Figure 8. The proposed retrofit program was to have been completed in 1976, but was never implemented. However, the Navy has made significant progress in retrofitting smokeless combustors to previously Smoky engines. Through contacts with Navy personnel (Reference 23), the status and costs of the current Navy retrofit program were obtained. As shown in Table 7, the J52 and TF30 retrofit programs are nearly complete. The J79 retrofit program is moving ahead although it is behind the original schedule proposed in 1972. The J57, TF41 and T56 engines have not been retrofitted due to a number of factors, including:

- Problems in meeting performance and durability goals with some engines, such as the TF41, has delayed consideration of modifications to reduce smoke
- Some engines, such as the J57, will be phased out and therefore the capital investment to retrofit them is not economically justifiable at this time
- Some design changes to reduce smoke levels have been unsuccessful for certain engines

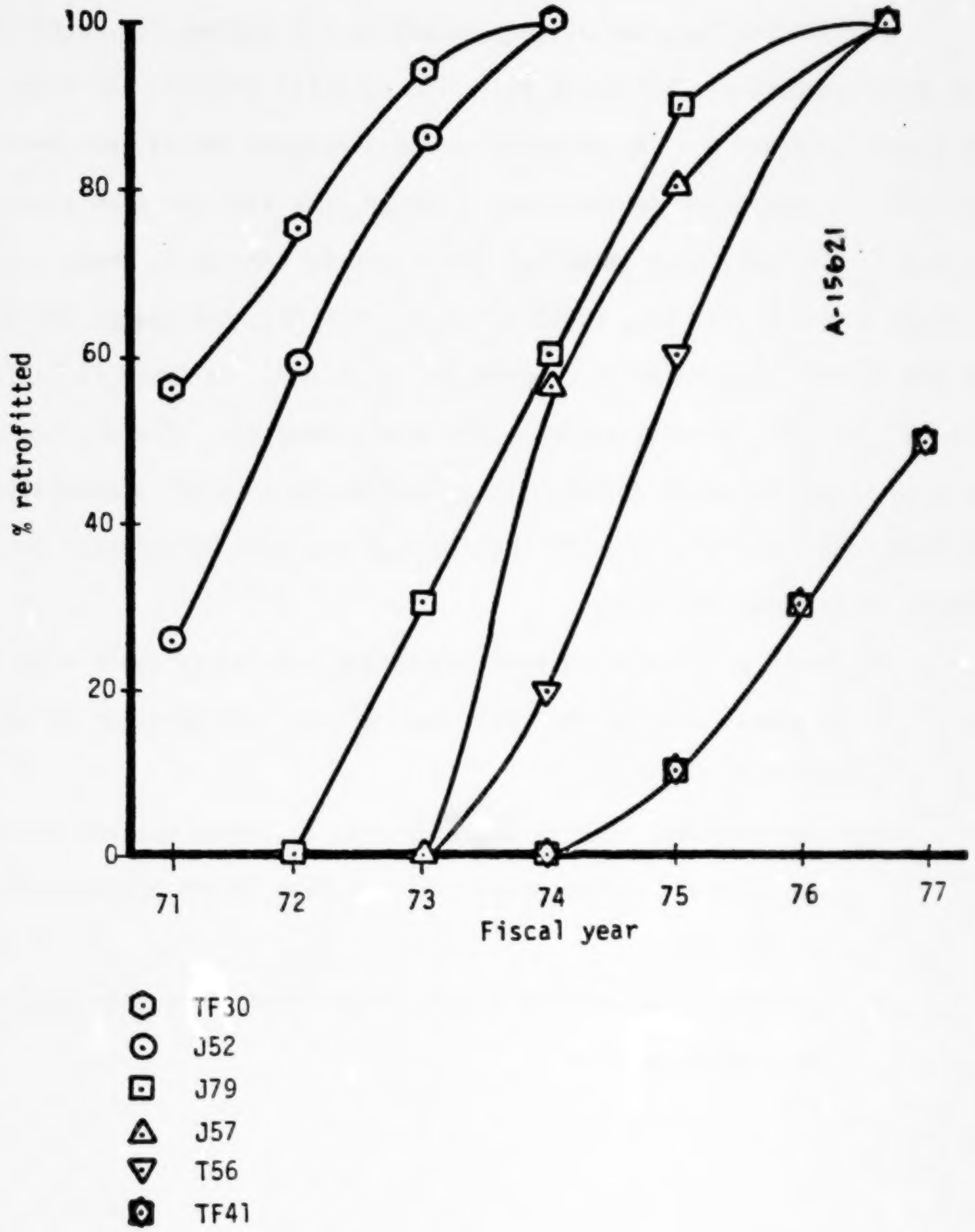

Figure 8. Navy estimate of smokeless burner retrofit schedule (Reference 21).

TABLE 7. CURRENT STATUS OF THE NAVY RETROFIT PROGRAM AND RETROFIT COSTS

Engines to be Retrofitted	Retrofit Cost Per Engine	Number of Engines Retrofitted	Number of Engines Left
J52-P8A retrofitted to P8B	$ 1,500	1135	6
TF30-P6C retrofitted to P6E	13,000	343	17
J79-GE10/10A retrofitted to GE10B	40,000	200	700

In summary, 40 percent of Air Force and 65 percent of Navy jet engines will be smokeless by 1985. These percentages reflect new "smokeless" combustor engine procurements and a limited amount of retrofitting to older engines. The Navy retrofit program has cost $6.2 million to date and will cost roughly $38 million when completed around 1981 (Reference 29). The Air Force TF 39 program is complete and has cost $2.9 million. Extensive retrofitting of smokeless combustors and faster retirement of smoky engines could result in much higher percentages of smokeless engine operations. However, the cost of extensive retrofitting and early engine retirement is large.

SECTION 3

WET-PACKED SCRUBBER COST ESTIMATES

In this section three widely different wet packed scrubber cost estimates are examined to determine the source of cost differential between these estimates.

The Aerotherm Phase I study (Reference 1) indicated that a wet packed scrubber would effectively reduce jet engine test cell plume opacity and particulate emissions. However, the scrubber is expensive to install and operate. If a cost-versus-benefit analysis were to be made for the scrubber system, accurate cost information would be required.

In Phase I, cost estimates for retrofitting scrubbers to type A* test cells were requested both from the Navy and a private contractor. The cost estimate was to be based on the following conditions:

- The scrubber was to be retrofitted to a Type A, permanent test cell
- A complete facility was to be provided -- including a scrubber, a cooling tower, a water cleanup plant, all site modifications, and installation of all equipment
- Costs of bringing utilities (water, electric power) to the test cell site were not to be included

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*Large, permanent concrete structures capable of testing engines in the 20,000-lbf thrust class.

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Three cost estimates were received: two independent estimates from the Navy, one estimate from a private contractor. The estimate prepared by the Naval Air Systems Command (Reference 32) in early 1975 is shown in Table 8, and the estimate prepared in January 1976 by the Naval Air Rework Facility (NARF), Jacksonville is shown in Table 9. A summary of the cost proposal prepared by the original system contractor for the Jacksonville prototype scrubber, Teller Environmental Systems, Incorporated, (TESI) is given in Appendix A. Since these estimates were prepared in 1975 or the first month of 1976, it has been assumed that the costs are in terms of fiscal year 1975 dollars.

A summary of bottomline costs is given in Table 10. These estimates differ by roughly a factor of 3. This wide differential in estimated cost prompted a critical examination of the cost estimates and conversations with personnel involved in preparing the original cost estimates. The results of our investigation are described below.

The TESI wet packed scrubbers consist of three main parts: (1) a jet exhaust pretreatment section where water vapor condenses on particulates, making them larger; (2) a packed-bed scrubber where the water-coated particles are transferred to the scrubber irrigation water; and (3) a water cleanup and sludge removal system. Since efficient transfer of particulates to scrubber irrigation water requires a certain volume of packed bed per cubic feet of test cell gas flowrate, scrubber volume is directly proportional to test cell gas flowrate. The test cell gas flowrate and corresponding mass flow is the sum of engine air and fuel flow, augmentor airflow, and quench water flow.* For a fixed thrust level,

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*Augmentor airflow and quench water flow are introduced into the jet exhaust gases to cool them so that heat damage does not occur to test cell acoustic baffles and concrete stack.

TABLE 8. SCRUBBER RETROFIT COST ESTIMATE -- NAVAL AIR SYSTEMS COMMAND

Item	Cost
Packed scrubber	$ 515,000
Cooling tower basin	160,000
Cooling tower	250,000
Water system for irrigation and quench	280,000
Water treatment plant	160,000
Exhaust stack modifications	50,000
Electrical work	100,000
Total	$1,515,000

TABLE 9. SCRUBBER RETROFIT COST ESTIMATE -- JACKSONVILLE NARF

Item	Cost	
1. Cooling tower well	$ 31,138	
2. Water treatment system	250,000	
3. Scrubber and quench water system including cooling tower	731,000	
4. Cooling tower and water treatment stairs	21,995	
5. Water treatment building (miscellaneous)	1,560	
6. Columns, beams, and miscellaneous for cooling tower pipe support	60,450	
7. Cooling tower and water treatment building -- general construction work	251,515	
8. Upper concrete work for scrubber enclosure including additional foundation	250,000	(due to pollution abatement) Prorated from a larger figure
9. Addition piles for building structure	40,000	(due to pollution abatement) Prorated from a larger figure
10. Extra electrical work on outside and inside of cell	307,077	(due to pollution abatement) Prorated from a larger figure
TOTAL	$1,944,735	

TABLE 10. COMPARISON OF SCRUBBER COST ESTIMATES

Estimate	Complete Cost One Cell Retrofit
Jacksonville NARF	$ 1,944,735
Naval Air Systems Command	1,515,000
Teller Environmental Systems, Inc.	705,650

engine airflow can vary significantly, depending on whether the engine is a jet with high average exhaust velocity (low mass flow) or a turbofan with lower average exhaust velocity (high mass flow). Depending on test cell and engine design, test cell airflow and the required scrubber volume can vary significantly even for a fixed engine thrust. Assuming that the scrubber cost is proportional to scrubber volume,† the cost can vary significantly with the test cell airflow. Based on this conclusion, we reexamined the original cost estimates, using test cell flowrate as our basis for comparison.

Teller Environmental Systems, Incorporated, based their cost estimate for the scrubber on a J79 jet engine operating with maximum afterburner (17,500-lbf thrust). The engine gas flowrate at this condition is roughly 180 lbm/sec. Turbofan engines such as the TF41 and TF30 have larger flowrates -- roughly 260 and 240 lbm/sec, respectively -- and would require larger scrubbers. Also, future engines might be even larger, making the TESI scrubber cost based on a J79 engine lower than the cost of the scrubber required for a cell that tests all military engines.

In addition to basing their costs on a J79, TESI also included in their estimate a modified augmentor which was projected to reduce the augmentor to engine airflow ratio to 0.6. This would reduce the total test cell gas flow, which, in turn, would minimize the size and cost of the scrubber required to clean up the exhaust.

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†Uninstalled costs of smaller units (10,000 to 20,000 cfm) vary with the 0.87 power of gas flowrate. For simplicity, a power of 1.0 is assumed to apply for large scrubbers (Reference 33).

The Navy is currently constructing four new test cells with wet packed scrubbers. These cells can handle engines producing test cell gas flows* of up to 770 lbm/sec. From conversations with Navy personnel who produced the original cost estimates, it is apparent that these cost estimates were based on these very large test cells. The estimate prepared by Jacksonville NARF personnel is based on a test cell gas flowrate of 660 lbm/sec (Reference 34). The Naval Air Systems Command estimate is based on an engine flowrate of approximately 350 lbm/sec (Reference 35). Assuming that a reduced test cell augmentor to engine air flow ratio of 1 can be achieved, the total test cell flowrate for this system is then 700 lbm/sec. Both test cell flowrates are much larger than the flowrate used in the TESI estimate.

In these cost estimates, the most expensive component is the scrubber and quench water system, including the cooling tower. Assuming that the cost estimates for the scrubb[illegible]d cooling tower system are directly proportional* to the test ce[illegible]rate, the estimate should be in the ratio of the flowrates. When the costs are scaled to the Jacksonville test cell flowrate of 660 lbm/sec, good agreement is achieved for the cost estimates for this portion of the system, as shown in Table 11.

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*All flows will be given exclusive of quench water flows.

*This assumption should be adequate, since NASC and Jacksonville NARF flowrates are close and TESI cooling tower costs were based on prorating a large single tower to two small test cells.

TABLE 11. COMPARISON OF SCRUBBER AND COOLING TOWER COST ESTIMATES, SCALED TO A 660 LBM/SEC FLOWRATE

	Jacksonville NARF	NASC	TESI
Test cell flowrate (lbm/sec)	660	700	288
Ratio of flowrates to Jacksonville NARF test cell flowrate	1.0	1.06	0.44
Original cost estimate ($1000)			
Scrubber	--[a]	515	184[b]
cooling tower	--	250	138[b]
Subtotal	731	765	322[b]
Scaled cost based on 660 lbm/sec ($1000)			
Scrubber	--	486	419[b]
Cooling tower	--	236	313[b]
Subtotal	731	722	732[b]
Percent difference		(-1%)	(+0%)

[a] Information not supplied with estimate.

[b] Includes contingency costs.

Thus, the large difference in flowrates can account for the differences in costs for the wet packed scrubber and cooling tower portion of the costs. The cost differentials for the other components in the scrubber system are not so easily reconciled.

Cost estimates for the water delivery and treatment, electrical, and structural systems are scaled to a 660-lbm/sec scrubber system consistant with the scrubber and cooling tower cost comparisons, and compared in Table 12. These costs are scaled directly with the scrubber flowrate. A more precise scaling approach is to make subcomponent cost proportional to flowrate to some exponential power which varies roughly between 0.6 and 1.0, depending on the subcomponent. This more precise approach was not taken here, since a subcomponent breakdown was not available and only broad component categories were given in the estimates.

The cost of water treatment depends upon the method used, and the estimates do not contain enough information to determine the differences between the water treatment systems. In addition, there is insufficient information to establish the cost of the irrigation and quench water delivery system for the Jacksonville NARF estimate. Keeping these caveats in mind, costs for water delivery and treatment systems scaled to a 660-lbm/sec scrubber system are compared in Table 12. The agreement between the scaled costs is poor. The Jacksonville estimate is low since water delivery costs were not included. However, an overall total system cost comparison which includes water delivery will better demonstrate the consistency of these cost estimates.

TABLE 12. COMPARISON OF WATER DELIVERY AND TREATMENT SYSTEMS, ELECTRICAL AND STRUCTURAL COST ESTIMATES, SCALED TO A 660-LBM/SEC FLOWRATE

	Jacksonville NARF	NASC	TESI
Ratio of flowrate to Jacksonville NARF test cell flowrate	1.0	1.06	0.44
Water Delivery and Treatment Systems			
Original cost estimate ($1000):			
Irrigation and quench	--[a]	280	--
treatment	272	160	-
Subtotal	272	440	158[b]
Scaled cost based on 660 lbm/sec ($1000)	272	415	359
		(+53%)	(+32%)
Electrical Systems			
Original cost estimate ($1000)	307	100	93
Scaled cost based on 660 lbm/sec ($1000)	307	94	212
		(-69%)	(-31%)
Structural Costs			
Original cost estimate ($1000)	635	50	0[c]
Scaled cost based on 660 lbm/sec ($1000)	635	47	0
		(-93%)	(-100%)

[a] Information not supplied with estimate.

[b] Includes contingency costs.

[c] A small structural cost is included in scrubber cost estimate.

A comparison of electrical system costs for a 660-lbm/sec scrubber system is also included in Table 12. This shows Jacksonville's estimate to be much higher than the NASC and TESI figures. However, conversations with Jacksonville personnel (Reference 34) have indicated that the cost for an electrical substation has been included in their estimate. Also, the Jacksonville estimate is based on prorated costs for a new test cell and scrubber system. Usually several contractors are involved in constructing a complete test cell and scrubber system, so it is difficult to separate out the costs associated with the scrubber from those of the test cell. (The prorating basis used in the Jacksonville estimate is not known.) In light of these factors, the large difference in costs between the Jacksonville and the other estimates is not surprising.

Structural costs estimated by Jacksonville personnel also are much higher than those estimated by NASC and TESI. The prorated Jacksonville estimate has a much larger construction expense for the scrubber system than NASC and TESI estimate. Expenses for concrete structures to house water pumping and treatment equipment have been included in the Jacksonville estimate, whereas only minor modification costs are included in the NASC estimate and no separate costs for structures have been included in the TESI estimate.* Jacksonville personnel believe that a significant amount of structural expansion and modification are required to support and house the scrubber equipment. Because it includes the electrical substation costs and a substantial proration of structural expenses to the scrubber system, the Jacksonville estimate is probably high relative to the other estimates. Therefore, the Jacksonville electrical and structural expenses have been removed from the original estimate and the total scaled costs then compared with the other estimates.

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*A small structural cost has been included in the scrubber cost estimate.

In Table 13 the adjusted cost estimates are compared for a scrubber system of 660-lbm/sec mass flow, and as anticipated, the Jacksonville adjusted estimate is now lower than the others. However, the estimates are all within 30 percent of each other. Also included in Table 13 is a comparison of the bottomline cost figures given in Table 10, scaled to a scrubber system of 660-lbm/sec mass flow. By including substantial structural and electrical substation costs, the Jacksonville estimate is once again higher than the others, but all of the estimates are still within 30 percent of each other.

In summary, the wide differences noted between Navy and private contractor scrubber cost estimates are based primarily on the difference in test cell mass flow used for the estimates. Furthermore, the Jacksonville estimate of scrubber cost contains electrical substation and structural equipment housing charges prorated from new construction costs which were not included in the NASC and TESI estimates. These costs are substantial and can result in either a positive or negative 30-percent difference between the estimates -- depending on whether these costs are included or deleted in the Jacksonville estimate. Based on simple scaling of the original cost estimate, it is believed that a 660-lbm/sec test cell gas flow scrubber system which includes water treatment can be constructed for approximately $1.3 million (fiscal year 1975 dollars). Inclusion of electrical substation and other power source costs could increase this estimate by $0.1 million.

TABLE 13. COMPARISON OF TOTAL SCRUBBER SYSTEM COSTS SCALED TO 660-LBM/SEC FLOWRATE

	Jacksonville	NASC	TESI
Cooling tower and scrubber	731	722	732
Water delivery and treatment	272	415	359
Electrical	--	94	212
Structural		47	0
Total	1003	1278	1303
% difference		(+27%)	(+30%)
Bottomline costs ($1000)	1945	1515	706
Scaled cost based on 660 lbm/sec ($1000)	1945	1429	1605
% difference		(-27%)	(-18%)

SECTION 4

JET ENGINE TEST CELL ENVIRONMENTAL IMPACT SUMMARY

In this section the impacts of jet engine test cell (JETC) operations on the environment are discussed. JETC emissions data currently are limited in quantity and quality, as well as highly dependent on engine type, operation mode, test cell configuration, augmentation airflow, and method of sampling. Therefore, jet engine exhaust emissions data are used to estimate uncontrolled JETC emissions. The exhaust emissions data are more plentiful and relatively more reliable than JETC emissions data, but they also are higher and, thus, represent maximum or worst-case conditions.

A mix of jet engine exit and JETC stack data is used to define emissions reduction effieiencies for three emission control methods: wet packed scrubbers, clean (smokeless) combustors, and ferrocene fuel additives. These methods represent strategies for post-test cell cleanup, internal engine combustion modification, and cleanup by altering fuel combustion characteristics, respectively. The variability of jet engine and test cell characteristics and the sparseness of emissions data for controlled jet engines makes it difficult to assess the effectiveness of these control techniques, and firm conclusions on controlled JETC emissions await better emissions data.

Research on the air quality impact of test cells and military base operations is currently being conducted by the Air Force and should be available in late 1977. The results of this study should be very valuable in assessing the impact of JETCs on several Air Force and Navy bases.

Presently, it is not possible to arrive at broadly applicable conclusions on the environmental impact of JETC operations since engines, duty cycles, test cells, and sites vary. Therefore, this report focuses upon one specific site: the JETCs of the Alameda Naval Air Rework Facility (NARF), California. By analyzing this site, problem areas needing further investigation are identified.

4.1 SITE LOCATION

To determine the environmental impacts of JETC operations, the Alameda Naval Air Rework Facility (NARF) was chosen as a "worst-case" condition. The Alameda NARF is a jet engine overhaul facility where extensive post-maintenance jet engine testing is carried out. Since it is located in the San Francisco Bay Area (population 4,781,000 in 1974), it has the potential for impacting large numbers of people. The base is located on the East Bay in a highly-developed area with a high level of pollution. The Oakland Harbor, I-80, I-680, Oakland International Airport, Peralta College, College of Alameda, Alameda City Administration buildings, and a residential section of the city of Alameda are all in the vicinity of the base.

Fifteen test cells and one test stand (Reference 36) are located on the base. Ten of the cells are depot-level cells and five are auxiliary power unit cells. An example of a depot-level cell is given in Figure 9. This type of test cell is used for testing engines after major maintenance or overhaul. A complete description of test cell operation and characteristics is given in the Phase I Aerotherm report (Reference 1). Based on a report issued in 1975, Alameda JETC operations (on an average annual basis) consist

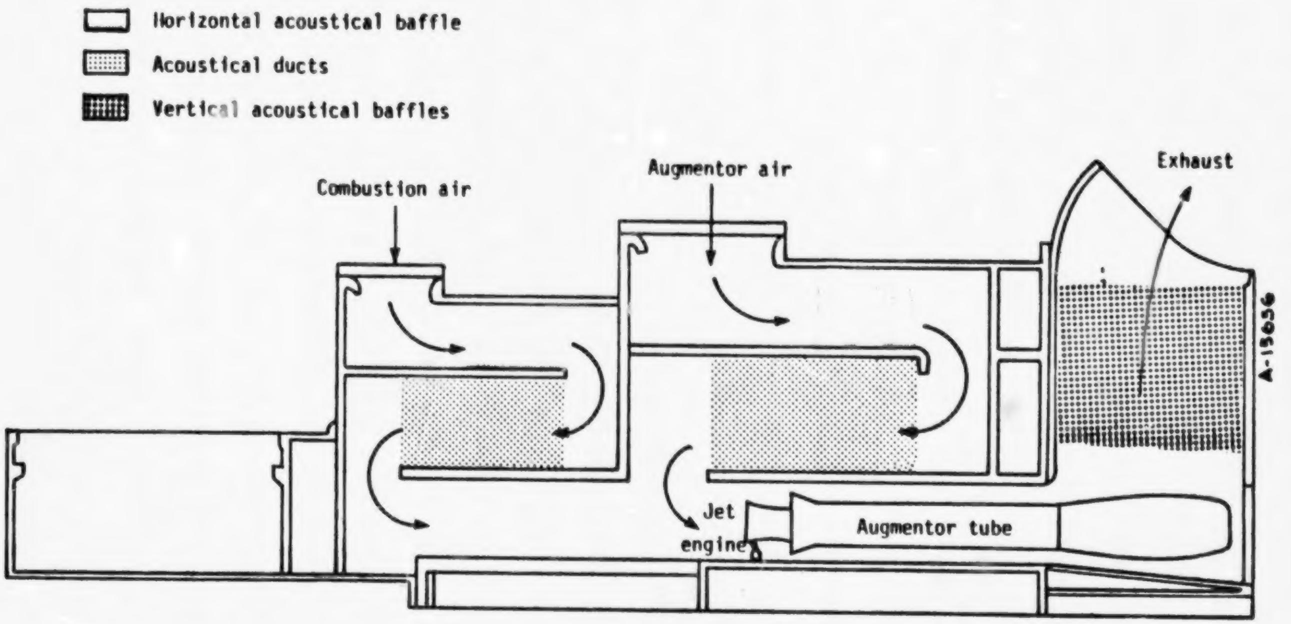
Horizontal acoustical baffle
Acoustical ducts
Vertical acoustical baffles
Combustion air
Augmentor air
Exhaust
Jet engine
Augmentor tube
A-15656

Figure 9. Tinker Air Force Base J79 engine test cell (Reference 37).

of five and a half tests per day of 3 hours duration (Reference 36). These tests consist of roughly 62-percent aircraft propulsion unit testing and 38-percent auxiliary power unit testing. Air quality modeling data for Alameda is available from the Navy (Reference 36), and the Air Force is in the process of modeling this and other bases, using their sophisticated Air Quality Assessment model. The results of these modeling efforts should provide useful data to assess JETC emission impacts on the environment.

4.2 UNCONTROLLED TEST CELL EMISSION AIR QUALITY IMPACT

The ultimate impact of a pollution source is on air quality within the entire region. However, regulations are applied on a source basis, because individual source contributions can be monitored. Therefore, this study will consider the environmental impact of JETCs on the basis of both source emissions and ambient air quality.

4.2.1 Gaseous and Particulate Emissions

Documented emissions data are very sparse. The emphasis on emissions data has been for aircraft operations rather than test cells, and as a result, only limited testing has been conducted on actual cells. Limited tests on JETCs indicates that the chemical composition of gaseous emissions remains relatively unchanged and particulates are reduced from engine exit to test cell stack exit (Reference 38). Several mechanisms are responsible for reducing particulate stack emissions from jet engine exit values. Quench water, which cools the exhaust, scrubs some particulate out of the exhaust stream -- as much as 50 percent for a scrubber-equipped cell with roughly 20 percent more quench water flow than a typical cell (Reference 39). (It should be noted that for some cells and some operating conditions no quench water is used.) Agglomeration and subsequent fallout within the cell and plating out on cell surfaces are additional modes of reduction (Reference 39).

Particulate emissions data obtained to date on JETC exhaust stacks tend to be unreliable, primarily because the large stack area and nonuniformity of flow velocities across the stack make isokinetic particulate sampling difficult. Some test cells even have recirculating flow regions in portions of the stack exit, making isokinetic sampling impossible or not meaningful. Therefore, jet engine exhaust data are used to estimate particulate emissions from uncontrolled JETCs. Other problems in measuring particulate are discussed in the phase I JETC report (Reference 1).

Since the chemical composition of gaseous emissions are relatively unchanged by the test cell, the engine exhaust gaseous emissions will be a close estimate of JETC emissions on a mass-per-hour basis. The engine exhaust particulate emissions are conservative because of the fallout of particulate within the test cell, and therefore, engine data represent worst-case particulate releases from test cells.

4.2.2 Uncontrolled Test Cell Plume Opacity

JETCs have been cited for noncompliance to local air pollution control district opacity regulations. Therefore, a complete evaluation of the environmental impact of JETC requires that plume opacities and their control be examined.

Many factors influence the opacity of a JETC exhaust. For example, augmentor and entrained air reduce opacity by diluting the stack particulate/gas mixture. For the same particulate emissions, a large-diameter test cell stack will provide a longer light-scattering path than a small diameter stack thereby giving a higher apparent opacity (Reference 40). Weather, sun angle, observer location, and other variables (Reference 40) can introduce a variation in Ringelmann number (RN) for a given exhaust flow particulate loading and size distribution.

Actual exhaust opacity readings for "smoky" jet engines can be as high as 2.5 RN (Reference 5). The diameters of the most effective light-scattering particles (those that create high plume opacity readings) range from 0.2μ to 2.0μ (Reference 40). Smoky engines produce particle sizes in this range during high power operations (References 5, 42). At low power settings, measurements indicate that after the exit, condensed hydrocarbon particles agglomerate to 10μ in diameter (Reference 5). These particles contribute little to the exhaust opacity.

At the JETC stack exit, particles range up to roughtly 2μ in diameter, 20 to 30 percent by weight are less than 1μ in diamter and 80 to 90 percent by number count are less than 1μ (References 43, 44). Most of the particulate is in the highly visible range and stack exit opacity readings can be as high as 3.0 RN for some "smoky" engines. In summary, because JETC exhausts have particle sizes in the highly visible range, high plume opacity readings result for test cell operations with "smoky" engines.

For a given uncontrolled JETC, exhaust opacity can be roughly correlated with smoke number and particulate density. These correlations indicate what change in particulate loading can be expected for a given change in exhaust opacity. In this study, such correlations were useful in assessing whether an exhaust opacity control device reduces the particulate loading or simply alters the particulate size distribution to the less visible range. This will be discussed further in the section on controlled JETC emissions.

The Navy has reported correlations (Reference 21) between SAE smoke number, particle grain loading, and Ringelmann number for conventional and smokeless engines (Figures 10 and 11). When grain loading data is not available, the Navy uses these correlations to convert Ringelmann numbers to grain loadings (mg/cu meter). These correlations are for dry catch only and are not valid at low power or idle where substantial condensed unburned hydrocarbons exist.

The reliability of the Navy correlation is checked in Figure 12 by plotting the Navy data with a curve based upon light-scattering theory. The anchor point for the light-scattering curve was obtained in Reference 40 by arbitrarily assigning an 85-percent opacity level to a 0.05 gr/scf particulate plume of mean particle diameter of 2.5μ from a power plant stack with a 32.5-foot diameter. The rest of the sigmoid curve is generated by applying the light-scattering theory for different grain loadings. The Navy data and the theoretical line have similar slopes, which lends some credibility to the use of the correlation.

4.2.3 Comparison of Jet Engine Emissions Data

The JETC emissions data used in this study and listed in Table 14 were extracted from a Navy Aircraft Environmental Support Office (AESO) air quality report (Reference 36). These data were originally obtained from the Aircraft Engine Emissions Catalog, (Reference 45). These data are generally within ±50 percent of published data for the J79 and J57 engines (Reference 41, 42), and within 15 percent for the TF30 engine (Reference 41). The AESO values are conservative for particulate and nitrogen oxide (NO_x) emissions, while hydrocarbon (HC) and carbon monoxide (CO) emissions can be either conservative or high, depending upon the engine type.

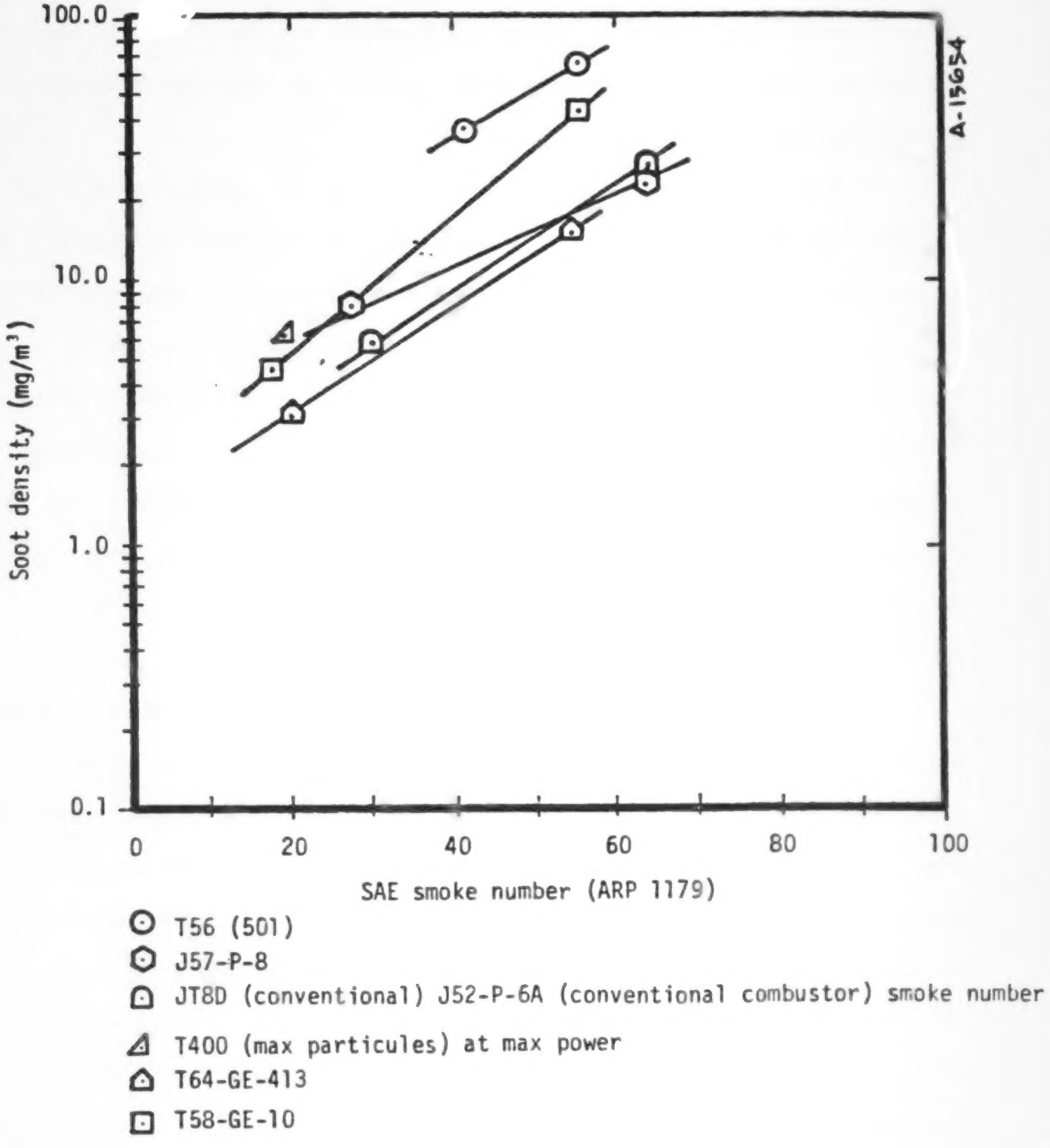

Figure 10. Relationship between smoke number and soot density (taken from Reference 21).

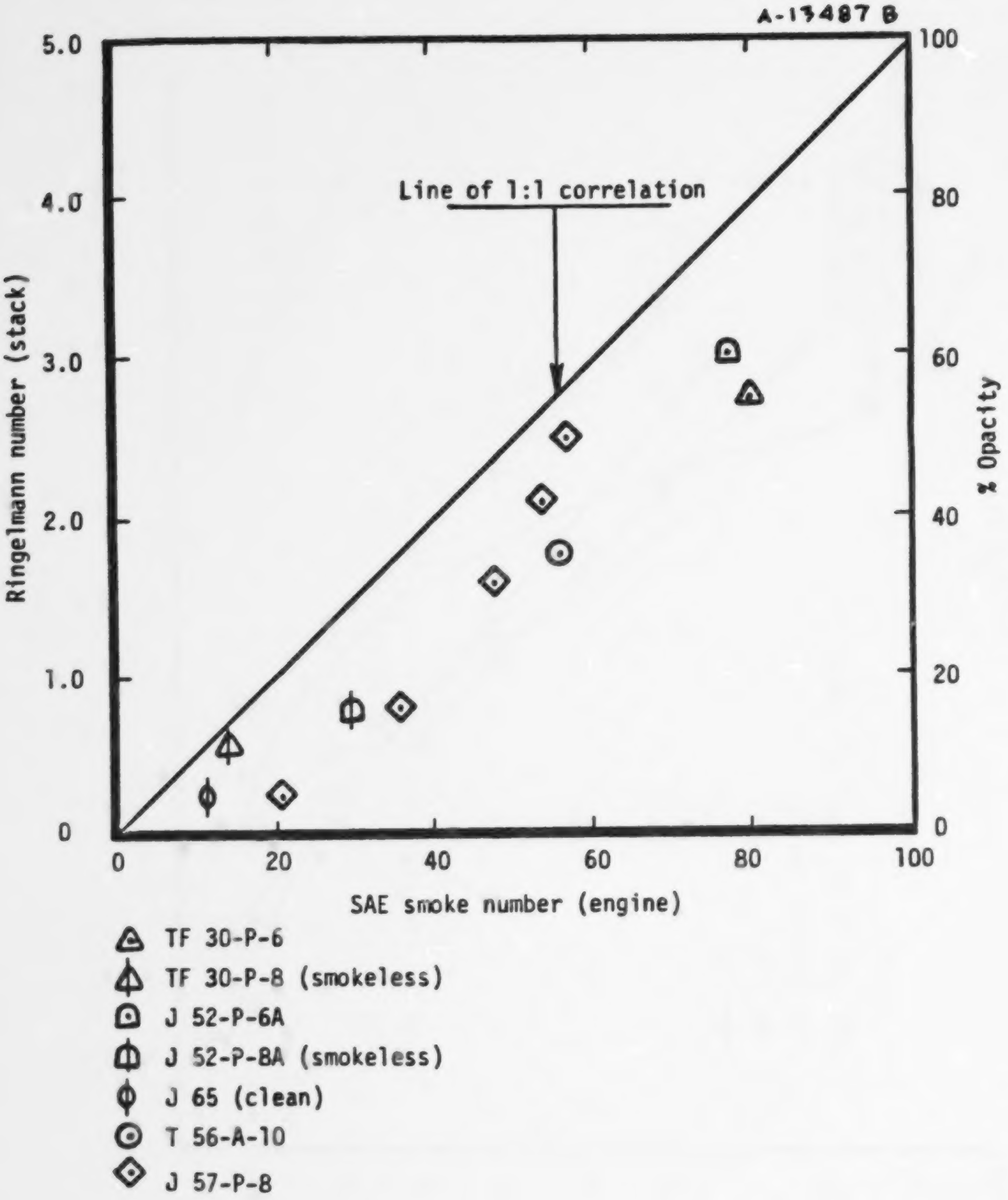

Figure 11. Smoke number versus Ringelmann reading for a 14-foot diameter stack (taken from Reference 21).

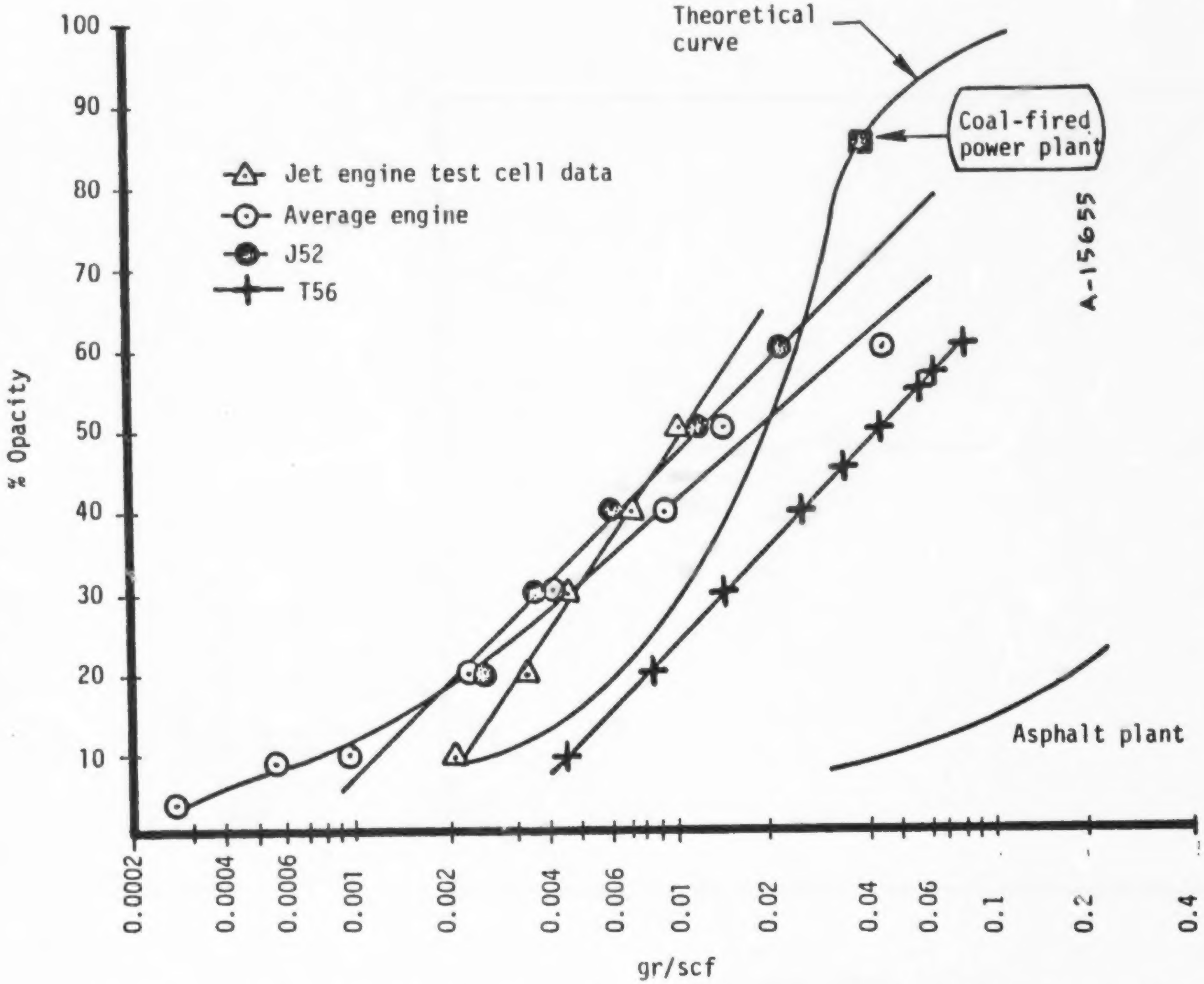

Figure 12. Theoretical and experimental opacity versus grain loading (Reference 21, 40).

TABLE 14. WORST-CASE JETC SOURCE STRENGTH DATA FOR ALAMEDA NARF (REFERENCE 36)

Engine	Percent Operational Time in Mode				Source Strength (lbs/hour)				
	Idle	Military	Other	A/B	CO	NO_x	UHC	Part	SO_x
J65	5	70	25	--	53.6	37.2	1.4	19.9	52
J52	10	65	25	--	12.1	60.7	9.3	176.1	52
J52	10	65	25	--	12.1	60.7	9.3	176.1	52
J52	10	65	25	--	12.1	60.7	9.3	176.1	52
T56	20	50	30	--	11.0	16.7	4.1	1.1	12
T56	20	50	30	--	11.0	16.7	4.1	1.1	12
TF34	10	50	40	--	13.6	25.5	3.8	8.8	115
TF34	10	50	40	--	13.6	25.5	3.8	8.8	115
TF41	10	70	20	--	33.9	150.0	17.9	127.3	72
TF30	5	65	30	--	18.9	121.0	7.4	113.6	72
GTCP	25	55	20	--	9.7	1.4	5.7	0.6	2
GTCP	25	55	20	--	9.5	1.3	5.6	0.6	2
GTCP	25	55	20	--	9.7	1.4	5.7	0.6	2
GTCP	25	55	20	--	9.5	1.3	5.6	0.6	2
T62	30	45	25	--	3.7	0.4	2.2	1.3	13

4.2.4 Comparison of Total Alameda JETC Source Emissions with BAAPCD Source Inventory

The Alameda individual JETC data have been combined to establish the total emissions from JETC operations. Consistent with the AESO report (Reference 36), the five auxiliary power unit test cells have been combined with the 10 depot-level cells to establish the emission source levels for all test cell operations at Alameda. Each cell emission value is multiplied by the number of tests per year and the duration of a test for each engine type. The ton/day values are summed over all 15 cells to arrive at the total emissions. It should be noted that the AESO report (Reference 36) from which engine emissions and test schedule data were taken, focused on worst-case conditions for air quality modeling. The total emissions given here are probably greater than those found on an "average" day at Alameda. Also SO_x emissions are based on the maximum allowable fuel sulfur content of 0.4 percent. The actual fuel sulfur content may only be a fraction of this value.

Table 15 is a comparison of Alameda test cell emissions and source emission values for the nine county Bay Area Air Pollution Control District (BAAPCD) (Reference 46). The jet engine test cell emissions also are compared with those from air carriers and military aircraft in this table. It can be seen that JETC operations at Alameda contribute less than 0.01 percent to UHC and CO, 0.07 percent to NO_x, 0.12 percent to SO_x and 0.26 percent to particulate in the total emissions inventory for the nine county BAAPCD. Comparison with total military aircraft operations emissions indicates that the Alameda NARF JETC operations contribute approximately 11 percent of particulate, 1 percent of UHC, 1 percent of CO, 10 percent of NO_x and 56 percent of SO_x emissions. It should be noted that of the four air bases in the nine-county area, Alameda has the lowest total percent emissions as is indicated in Table 16.

TABLE 15. COMPARISON OF WORST-CASE ALAMEDA JETC EMISSIONS TO NINE COUNTY BAAPCD EMISSION SOURCE INVENTORY AND MILITARY AND CIVILIAN AIRCRAFT OPERATIONS

	Part (ton/day)	UHC (ton/day)	CO (ton/day)	NO_x (ton/day)	SO_x (ton/day)
Alameda (Reference 36) 1974 JETC	0.47	0.07	0.17	0.48	0.31
BAAPCD (Reference 46) 9 County Avg.	180	1000	4300	720	270
Air Carriers[a]	5.4	10	21.5	7.92	0.81
Military Aircraft[a]	4.3	8	21.5	5.04	0.54

[a] Contributions of these categories to total county emissions (% contribution x 9 county average)

TABLE 16. PERCENT EMISSION CONTRIBUTIONS OF BAAPCD MILITARY AIR BASES

Base	Percent of Total Emissions	Part (percent)	HC (percent)	CO (percent)	NO_x (percent)	SO_x (percent)
Alameda	8.6	10	11	13	9	--
Hamilton	12.6	13	16	20	14	--
Moffett	30.2	30	29	28	31	33
Travis	48.6	47	44	39	46	67
	100.0	100	100	100	100	100

4.2.5 Comparison with BAAPCD General Combustion Source Regulations

Table 17 gives a comparison of JETC emissions with source regulations, listing the local BAAPCD General Combustion Source Regulations and uncontrolled worst-case Alameda test cell emissions developed from Table 14 and Reference 36. The worst-case emission levels listed in Table 17 are based on engines which produce the highest reported level of a specific emission or opacity during an average test cycle, as given in Table 14.

TABLE 17. COMPARISON OF MAXIMUM UNCONTROLLED JETC EMISSIONS TO COMBUSTION SOURCE REGULATIONS (REFERENCES 46, 36)

Emission	Standard BAPPCD	Alameda	Engine Type
Opacity	RN $\leq$ 1	RN $\cong$ 3	J52
Particulate (gr/scf)	0.15	0.04	J52
Total UHC (ppm)	300	107	T56
NO_x (ppm) >(250 MBtu/hr) source	225	174	T56
SO_x (ppm)	300	58	T56

The parts-per-million concentrations include augmentation air and are uncorrected for dilution. Because the values are averages for a test cycle which includes idle, as well as military and other power settings, these values are lower than peak values, and much lower than values corrected for dilution. However, they do represent a duty-cycle emission, and dilution air correction is not required by the BAAPCD. The opacity level is based on observation of a smoky J52 engine operating in a JETC (Reference 21). It is assumed that smoky J52 engines operating at Alameda would achieve the same level of opacity. The J52 engine is the highest (grains/scf) source of particulate and has the highest opacity of all engines tested at Alameda. During JETC operations, the T56 has the highest level of NO_x (on a volume basis) of all of the engines tested at Alameda.

Comparing the worst-case Alameda JETC opacity and emissions with BAAPCD regulations, it can be seen that only the opacity exceeds the general combustion source regulations. The three engines which probably exceed the opacity limit at Alameda are the J52, TF41, and TF30. Smokeless versions of the TF30 and J52 would not exceed the opacity regulation. Based on Alameda test cell operations reported in Reference 36, it can be concluded that roughly 40 percent of Alameda JETC operations are above the BAAPCD opacity regulations.

4.2.6 Air Quality Comparison

The Navy has applied the EPA "PTMPT" and "PTMAX" air quality models (Reference 47) to determine the impact of Alameda NARF JETC operations on local air quality (Reference 36). The models are Gaussian-based dispersion techniques that determine the spread and dilution of pollutants from a point source. The air quality models use as input the locations and strengths of emission sources and weather data. Contributions from multiple sources are superimposed to establish the total impact on ambient air quality. To obtain worst-case results, weather parameters were selected to achieve maximum ground concentrations outside the base perimeter. The results of this worst-case study are summarized in Table 18, listing measured background levels, calculated base perimeter maximum JETC contributions, and local and Federal air quality standards.

TABLE 18. IMPACT OF JET ENGINE TEST CELL EMISSIONS ON ALAMEDA COUNTY AIR QUALITY.[a]

Emission	Standards µg/m³		Alameda, µg/m³									
			Background Level	JETC Uncontrolled		JETC Controlled						
						Scrubber		Clean Combustor		Additives		
	BAAPCD	Fed Prim		max 1 hr	max 24 hr	1 hr	24 hr	1 hr	24 hr	1 hr	24 hr	
Part	60^e 100^d	75^e 260^d	105	27.6	3.5	6.1	1.8	.77	21.8	2.8	1.7	
UHC	--	160^c	6.5	22.5	2.8	22.5	2.8	22.5	2.8	22.5	2.8	
NO_x	470^b	100^e	70	33.5	4.2	33.5	4.2	50.3	6.3	33.5	4.2	
CO	11000^f 46000^b	40000^b	2000	49.3	6.2	49.3	6.2	49.3	6.2	49.3	6.2	
SO_x	105^d 1310^b	365^d 1310^c	13	35.1	4.4	35.1	4.4	35.1	4.4	35.1	4.4	

[a] Alameda Uncontrolled JETC values from AESO 111-75-8A, Table 4 (Reference 36)

[b] 1-hr concentrations not to be exceeded more than once per year

[c] 3-hr concentrations not be be exceeded more than once per year

[d] 24-hr concentrations not to be exceeded more than once per year

[e] Annual arithmetic mean

[f] 12-hr concentrations not to be exceeded more than once per year

From Table 18 it can be seen that all JETC emission contributions are beneath BAAPCD and Federal standards. For a duty-cycle normalized to a 1-hour base, worst-case UHC and SO_x emissions are greater than the background levels by 3.5 and 2.7 times, respectively. (Background here refers to ambient levels measured near the air base perimeter over a period of many hours.) On a 24-hour air quality comparison, the maximum JETC emissions represent the following percentages of local background levels: 3 percent of particulate, 43 percent of UHC, 0.3 percent of CO, 6 percent of NO_x, and 34 percent of SO_x. Worst-case test cell operations appear to contribute a large portion of UHC and SO_x to the background levels. Ground-level contributions upwind and downwind of this maximum point would be less.

4.3 CONTROLLED TEST CELL EMISSIONS AIR QUALITY IMPACT

If Alameda JETCs are considered as stationary sources, their operation with "smoky" engines would be in violation of local BAAPCD standards for stationary source opacity. Gaseous and particulate emissions would not exceed local source regulations. However, if the cells were in certain local regulating districts within the United States, which require emission corrections for dilution air, then some engine tests also would exceed NO_x and THC regulations.

In this section the impact of three control methodologies -- wet packed scrubbers, clean combustors, and ferrocene fuel additive on JETC emissions are discussed. The wet packed scrubber is an example of a post-engine-cleanup technique, whereas the clean combustor control method alters the combustion processes to reduce the engine exhaust emissions. Ferrocene, a fuel additive, chemically reduces JETC opacity and may reduce particulate loading.

Currently, these three control methods are used primarily to reduce particulates and opacity. However, one method -- clean combustors -- alters gaseous emissions. A detailed discussion can be found in the Aerotherm Phase 1 report (Reference 1) and the references cited in the following sections.

4.3.1 Gaseous and Particulate Emissions

Controlled JETC emissions data are very sparse and show a lack of consistency, which makes it difficult to assign a single reduction efficiency for each pollutant to a particular control technique. Thus, a single "average" efficiency for each pollutant has been applied to each control technique. It is expected that these efficiencies will not apply to every engine and test cell combination; however, since reasonable alternatives are not available, this approach has been taken.

4.3.2 Wet Packed Scrubber

A wet packed crossflow nucleation scrubber designed by Teller Environmental Systems, Incorporated, is currently in operation at the Jacksonville Naval Air Rework Facility. This scrubber removes particulates by:

- Injecting water directly into the exhaust jet, superstaturating the particle laden stream
- Condensing the water on the particles at a downstream location, making them grow in size
- Impacting the large water/particulate drops onto the stack-mounted, packed-bed scrubber section, depositing both water and particulate in the bed
- Carrying the particulate and condesned water out of the test cell by an irrigation water system

Through the scrubbing process, a considerable amount of particulate is removed, while some water vapor is added to the stream.

Some experimental emissions sampling has been conducted in the stack-mounted scrubber (Reference 44). However, the data taken are not necessarily representative of actual particulate concentrations since isokinetic conditions were not maintained during sampling. It is extremely difficult to sample the large, low-velocity face of the scrubber, even when local wind velocities are negligible. Because sampling is difficult and accurate emissions data are needed, a 1/50-scale model scrubber was constructed and attached to the Jacksonville Black Point No. 1 test cell which houses the full-sized scrubber. With the model scrubber, sampling conditions were carefully controlled and good data were obtained.

Details of the model scrubber sampling procedure are presented in the Aerotherm Phase 1 report (Reference 1). From these tests it has been concluded that the wet packed scrubber and quench water flow reduced the particulate concentrations from a J79 jet engine by roughly 78 percent (Reference 39). Also, no significant changes (less than 5 percent) in concentrations of CO, CO_2, NO, and NO_x across the scrubber were observed (Reference 39).

Even though full-scale scrubber tests could not supply detailed emission concentrations, they did provide relevant information on plume opacity (Reference 44). Observations of scrubber test cell plumes of smoky engines indicated that the wet packed scrubber can reduce plume opacity below Ringelmann 1 levels. It should be noted that the scrubber produces a large, dense white steam plume (ranging in size from several hundred up to 1500 feet) which may obscure a more dense particulate plume near the test cell stack exit. However, by the time the steam plume dissipates, the exhaust plume also is greatly spread out and the particulate plume is not visible. Besides obscuring particulate plumes, the steam plume might present a nuisance through coating all objects in the vicinity of the test cell with particle-laden drops (Reference 5). Nonetheless, wet packed scrubbers reduce plume opacity levels below Ringelmann 1 at distances beyond the steam plume.

Presently, four new scrubber-equipped test cells are under construction at Jacksonville. These will be large test cells which can handle engines with up to 350 pounds per second airflow. Each cell will be equipped with water cooling and particulate removal systems which will allow water to be recycled in a closed-loop. With the recycling system only 10 percent of the water flow needs to be made up while the system is operating. It is estimated that a maximum pumping capacity of 14,000 gpm will be required for these scrubbers, which translates into a significant energy consumption of 1200 kW (1500 kva). The cost of this power is the major nonlabor expense incurred by test cell operations. Annual electrical operating costs for the scrubber should be approximately $18,000, based on two engine tests per day, 250 operation days per year, maximum water flowrate, and a cost of 3.5 cents per kilowatt-hour. Actual maintenance and operating costs for the system would be several times this electrical cost.

4.3.3 Clean Combustors

This section focuses on the application of smokeless combustors to current military jet engines. To reduce exhaust opacity and particulate emissions from "smoky" engines, clean combustors use redesigned combustion chambers that eliminate conditions favoring pollutant formation. Early redesigns for military and civilian engines were directed twoards reducing exhaust opacity, whereas more recent civilian engine redesigns seek to reduce gaseous emissions as well as exhaust opacity. Modifying an existing engine to reduce emissions is far more difficult than designing a new engine with low emissions, and the same modification can produce quite different results on different engines. Therefore, engine modifications for pollutant reductions must be carefully tailored to the individual engine.

Exhaust opacity measurements on J52, TF30, and J79 engines indicate that smokeless combustors reduce plume Ringelmann numbers from a maximum of 2.5 to less than 1 (Reference 5). When all available opacity data are examined, opacities ranging from 26 to 80 percent are reduced to a range from 2.5 to 17 percent, an average reduction of 86 percent. As demonstrated by the data presented in Table 19, smokeless combustors can reduce opacities at all power levels.

TABLE 19. EFFECT OF SMOKELESS COMBUSTOR ON J79 PERCENT OPACITIES (REFERENCE 22)

Power Level	Smoky (percent opacity)	Smokeless (percent opacity)	Smoky/ Smokeless Ratio
Idle	26	2.5	10.4
90%	61	3.0	20.3
95%	62	8.0	7.8
Military	61	17.0	3.6
Average	53	7.6	10.5

Reductions in particulate concentration accompany the reductions in plume opacity. The smokeless combustor particulate data used in this study consist of particulate measurements on "smoky" and "smokeless" J52 engines.

Only a 21-percent reduction in particulate was reported for the J52 engine (Reference 24). However, it was indicated in Reference 24 that considerable differences in performance existed between the "smoky" and "smokeless" J52 engines, making a direct comparison of particulate reductions difficult. The opacity versus particulate correlation given in Figures 10 and 11 indicates a 94- to 98-percent reduction of particulates for several engines (References 21, 5, 22). Although particulate acutally is reduced by only 21 percent, the large apparent reduction indicates that clean combustors have probably shifted the exhaust particle size distribution out of the highly visible range. Extensive particulate and opacity data on smoky and smokeless versions of the same engine are needed to confirm this hypothesis. For this study, it is assumed that clean combustors reduce particulate concentrations by 21 percent.

Presently, smokeless combustor gaseous emission data is sparse. For this study, data from two commercial engines, JT3D, JT8D, and two military engines, TF39 and J79, were used to estimate the impact of smokeless combustors on gaseous emissions. The commercial engines, JT3D and JT8D, have some design similarities with the military J57 and J52 engines respectively, and these commercial engines exhibit uncontrolled gaseous emission levels which are comparable to the military engines.

A summary of the effects of smokeless combustors on gaseous emissions for the four engines are given in Table 20. The effect of "smokeless" combustors on gaseous emissions does not appear to follow consistent trends: unburned hydrocarbon and CO emissions seem to decrease or remain the same for military engines, while most nitrogen oxide emissions are increased. However, the increases in NO_x are scattered over a range from -0.6 to +100 percent.

TABLE 20. PERCENT CHANGE IN EMISSION LEVELS DUE TO SMOKELESS COMBUSTOR RETROFIT

Engine	THC (percent)	CO (percent)	NO_x (percent)	Smoke (percent)	Reference
JT3D	-47	-36	+47	-70	12
JT8D	-47	-21	-0.6	-53	25
JT8D	-37	-17	+64	-59	26
J79	+344	+404	+100	-62	22
TF39	0	0	+5	-94	27

To compare the clean combustor controls to wet packed scrubber and fuel additive controls, a single clean combustor reduction efficiency is assumed to apply to all engines for each pollutant. Due to wide scatter and conflicting trends, it is assumed that THC and CO emissions are, on the average, not altered by retrofitting smokeless combustors. For the increase of smokeless combustor NO_x emissions, a simple average of the percent increases in Table 20 gives an increase of 50 percent.

4.3.4 Ferrocene Fuel Additive

Additions of ferrocene to jet fuel have been observed to reduce opacity and particulate grain loadings of exhaust plumes (Reference 24). Several chemical mechanisms may have caused these decreases (Reference 41):

1. Shift in the combustion reactions to favor the formation of a low-visibility size range of particles. (In Reference 48 it was hypothesized that the electrons from the metal in the additive neutralizes ionic precursors of particulate material.)

2. The iron in ferrocene serves as an oxidation catalyst
3. The ignition temperature of soot is lowered
4. Particle growth is limited
5. The refractive index of the particles is altered

Some or all of these mechanisms may be working in jet engines in which ferrocene additives are used.

Depending on engine type, the weight percent of ferrocene additive in fuel required to reduce opacity to 20 percent varies from 0.02 to 0.1 (Reference 1). Increases above 0.1 wt percent do not show proportionate decreases in particulate emissions (References 24, 38). In one study, when particulates were collected by both EPA and LA sampling trains (Reference 38), ferrocene at 0.042 wt percent reduced particulate loadings 53 percent. Another study (Reference 24) showed that at higher power settings ferrocene reduced particulate concentrations 64 percent, whereas at idle settings it reduced particulate 45 percent. These values give an average reduction of 54 percent in particulates for ferrocene addition.

The trend of greater reduction at high thrust levels is also substantiated by Reference 49. It may be hypothesized that ferrocene addition only reduces soot formation, and therefore, the larger quantities of condensed unburned hydrocarbons at low power levels will not be affected. This mechanism is consistent with the lower effectiveness of ferrocene at low power levels. To compare control methods, ferrocene is assumed to reduce particulates 53 percent.

Ferrocene has been reported to eliminate visible plumes (References 48, 50). In Reference 41, ferrocene was reported to reduce jet engine plume opacities from RN 2.5 to 0.25 (600 to 1000 ppm Fe added). From these data, it can be assumed that (for the purposes of comparing control methods), ferrocene reduces jet plume opacities below RN 1.0.

None of the studies cited above listed both opacity and particulate data. It was thought that using the Navy correlation might increase the number of opacity and particulate readings upon which to draw a conclusion (known opacities could be converted to particulate concentrations and vice-versa). However, use of the correlation in this case does not appear to be valid. It was interesting to find that the opacity and particulate correlation presented in Figures 10 and 11 give unrealistically low particulate concentrations when the opacity levels with ferrocene addition are used. This indicates that the Navy correlation is not applicable for ferrocene addition. It may be conjectured that ferrocene is shifting the particle size distribution out of the highly visible range as well as reducing particulate concentrations. This would reduce the opacity beyond that expected by mass reduction alone.

Recent Alameda Naval Air Station tests have indicated that gaseous emissions of CO, SO_x, NO_x, and UHC remains essentially unchanged with ferrocene addition (Reference 23).

Ferrocene Toxicity

Ferrocene is the common name for dicyclopentadienyl iron, an organometallic compound with chemical formula $Fe(C_5H_5)_2$. Ferrocene is a crystalline material which breaks down thermally above 400°C and is soluble at 5 to 6 percent by weight in JP-5 fuel (Reference 51). As a control method, ferrocene is dissolved in a solvent and introduced into the fuel so that it is present during the combustion process.

The toxicity of ferrocene and its products has been of some concern. Ferrocene is slightly toxic (Reference 51). Animal studies showed little, if any, ocular irritation; abraded and unabraded skin irrigation tests were negative; and inhalation studies indicated no significant symptoms (Reference 51). Ferrocene is not toxic unless ingested. Ferrocene dissolved in xylene, toluene, and JP-5 fuel did not demonstrate a higher rat LD_{50} (50-percent mortality) than that of the solvent alone. The oral and intraperitoneal LD_{50}'s for a relatively pure sample* of ferrocene are 1890 mg/kg and 1520 mg/kg, respectively, which places ferrocene in the slightly toxic category (Reference 51).

The primary combustion products of ferrocene are water, carbon dioxide, and iron oxide. During combustion, the two cyclopentene rings separate from the iron and react, forming products indistinguishable from fuel combustion products.

The toxicity of the primary combustion products of ferrocene is minimal. Fe_2O_3 is the least toxic oxide of all the fuel additive oxides; it is only slightly toxic on an acute local basis, and is not toxic on a chronic basis (References 52, 53).

Even though iron oxide by itself is not a real concern, it has been hypothesized that iron compounds may serve as a transport mechanism into the body for combustion-formed carcinogenic agents (Reference 54). Furthermore, a recent EPA publication indicates that in boiler processes, iron may react with polycyclic organic material (POM) to produce a potentially carcinogenic substance (Reference 55). Another study on residual oil combustion (Reference 56) has indicated that POM's are reduced when ferrocene is used. At this time, it is not clear whether ferrocene products have the potential to transport carcinogenic POM's into the body or ferrocene products and POM's react to form a different substance. Further research is needed into combustion processes with ferrocene addition.

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*The ferrocene tested in this study was Arapahoe Chemical Company's Fe 55^R Smoke Suppressant. The introperitoneal rat LD_{50} data presented here are somewhat higher (indicating lower toxicity) than those reported by other laboratories with other sources of ferrocene.

Effect of Ferrocene on Jet Engines

Ferrocene is stable in jet fuel at low temperatures. At high temperature, (400-500^{0}F) a solid is formed which may clog fuel lines (Reference 1). This prevents ferrocene from being used during in-flight operations, since the fuel is a coolant and can reach very high temperatures. However, if the stationary JETC fuel supply system is properly designed, the ferrocene can be used without clogging.

Jet engines which have used the ferrocene additive show red deposits of varying thicknesses on the internal surfaces of the combustors. These deposits are composed primarily of iron oxide. For short periods of testing, on the order of 2 to 4 hours, the deposits do not affect the performance of most engines (References 50, 5, 57). However, Naval Air Propulsion Test Center studies of ferrocene addition have shown that out of eight engines, two engines (the T56 and J79) experienced a problem with engine deposits (Reference 57). Besides reducing engine performance, the deposits created by ferrocene addition may lead to problems with engine durability and in-flight safety of jet aircraft. These data indicate that ferrocene addition must be carefully evaluated on an engine-by-engine basis.

4.3.5 Controlled Test Cell Emissions Air Quality Impact

In the section on uncontrolled test cell emission it was concluded that several current military engines exceed local opacity regulations. In this section, the control method efficiencies previously derived are applied to the uncontrolled JETC emissions to determine the controlled emission levels. These emissions are then compared to the regulations. In Table 21, opacity levels and emission reductions achieved by wet packed scrubber, clean combustor and ferrocene fuel additive control methods are summarized. All methods can decrease plume opacities to the Ringelmann 1 level, while they reduce particulate concentrations from 21 to 78 percent. The only definite change in gaseous emission level is an increase in NO_x concentration when clean combustors are fitted to an engine.

TABLE 21. COMPARISON OF THREE CONTROL METHODOLOGIES -- RINGELMANN OPACITY AND PERCENT CHANGE IN EMISSIONS

	Opacity	Particulate	UHC	CO	NO_x
Wet Scrubber	<RN1	-78	--[b]	--[b]	--[b]
Clean Combustor	0.3 - 1.1 RN	-21	--[c] (-47,+344)[a]	--[c] (-36,+404)[a]	50 (0,+100)[a]
Ferrocene Fuel Additive	0.25 - 1 RN	-53%	--[b]	--[b]	--[b]

[a] Range of values for a number of engines

[b] Effect on gaseous emissions less than 5 percent

[c] Scattered data -- no reliable values can be assigned

4.3.6 Comparison of Controlled Total JETC Emissions with BAAPCD Source Inventory

Table 22 summarizes the impact of control techniques on Alameda total JETC emissions. As noted previously, total JETC source contributions are very small percentages of BAAPCD source emission inventory values. This same conclusion is reinforced by application of controls in all cases, except for NO_x generation with a clean combustor. Yet even here the increase is not substantial, and the conclusion reached for uncontrolled JETC operations is still valid.

4.3.7 Comparison of Controlled Emissions with BAAPCD General Combustion Source Regulations

In Table 23, the worst-case Alameda controlled JETC emissions are compared with BAAPCD local regulations. As in the uncontrolled case, gaseous emissions are below general combustion source regulations. However, NO_x concentrations under worst-case conditions for the clean combustor control method are now slightly above the regulations. Controlled plume opacity levels are roughly at or below the regulation level.

From the Alameda test cell operation schedule and emissions levels, presented in Reference 36 it can be concluded that the scrubber and additive control methodologies are able to meet the local emission regulations, including opacity. The clean combustor control method for the T56 engine meets all of the standards except NO_x concentrations. It is estimated that 9 percent of Alameda JETC operations would exceed the NO_x regulation if clean combustors were applied to the T56 engines.

4.3.8 Controlled JETC Air Quality Impact

As previously discussed, worst-case uncontrolled JETC operations make a substantial contribution only to UHC and SO_x ambient concentrations (roughly 43 and 34 percent, respectively, on a 24-hour basis) as shown in Table 18. Since these quantities are found to be unaffected by the control methods discussed herein, the conclusions reached for the uncontrolled JETC operations are also applicable to the controlled case. As can be seen in Table 18, contributions of both controlled or uncontrolled Alameda JETC operations to ambient air quality are far below BAAPCD or Federal regulations.

TABLE 22. EFFECT OF CONTROLS ON TOTAL EMISSIONS FROM JET ENGINE TEST CELLS AT ALAMEDA NAVAL AIR STATION

Emission	Tons/Day				
	BAAPCD[a] Average	JETC Uncontrolled	JETC Controlled		
			Wet Packed Scrubber	Clean Combustor	Fuel Additives
Part	180	0.47	0.10	0.37	0.22
UHC	1000	0.07	0.07	0.07	0.07
CO	4300	0.17	0.17	0.17	0.17
NO_x	720	0.48	0.48	0.72	0.48
SO_x	270	0.31	0.31	0.31	0.31

[a] County area -- average emissions, 1974

TABLE 23. COMPARISON OF MAXIMUM ALAMEDA CONTROLLED AND UNCONTROLLED JETC EMISSIONS WITH BAAPCD GENERAL COMBUSTION OPERATING REGULATIONS

Emissions	Standard	JETC Alameda Uncontrolled	Scrubber	Controlled Combustor	Additive
Opacity	RN $<$ 1	RN $\approx$ 3.0	RN $\leq$ 1	RN $\leq$ 1.1	RN $\leq$ 1
SO_2	300 ppm	58 ppm	58 ppm	58 ppm	58 ppm
Part.	0.15 gr/scf	0.04 gr/scf	0.009 gr/scf	0.032 gr/scf	0.019 gr/scf
Total HC	300 ppm	107 ppm	107 ppm	107 ppm	107 ppm
NO_x	225 ppm	174 ppm	174 ppm	261 ppm	174 ppm

4.4 JETC ENVIRONMENTAL IMPACTS ON WATER, SOLIDS AND PEOPLE

In addition to impacts on air quality, JETC operations have impacts on water and solid wastes which need to be considered. JETC operations also have been the subject of several nuisance complaints filed by people residing in the vicinity of military bases. To complete the environmental impact summary, these areas are briefly discussed below.

4.4.1 Uncontrolled JETC Water Quality Impact

Water is used during operations to quench or reduce the temperature of the jet exhaust so that the test cell acoustic baffles are not damaged. The quantity of water used varies according to engine type, power level and cell design. Quench water, particularly at idle, may not be used until stack temperatures indicate a need for cooling water. Typically, up to 700 and 1000 gpm of quench water are used for normal rated and military power levels, respectively (Reference 39). At these levels, most of the quench water exits via the stack as vapor or droplets. Ground release can occur at low thrust levels, but as drips rather than flow (Reference 39).

The quench water spary scrubs some particulate out of the gas stream in addition to condensing unburned hydrocarbon vapors. Some limited chemical analyses of quench water discharges have indicated that the filterable residues are water salts resulting from heating water in the augmentor tube (Reference 39). Nonfilterable residues are carbonaceous. The scrubber water is colloidal, and the particles are hydrophobic, possibly as a result of being coated with JP-5 or degraded JP-5 fuel (Reference 43).

Since actual water discharges are minor and can be contained without discharging into a sewer or larger body of water, the impact of JETC on water quality is insignificant.

4.4.2 Controlled JETC Water Quality Impact

Because the clean combustor control method has no water requirements or discharges beyond those of uncontrolled JETCs, conclusions reached for uncontrolled test cells apply to those controlled by clean combustors.

Wet packed scrubbers do not create any new problems of water discharge, since the 16,000 to 17,000 gpm of scrubber irrigation water for a production system is cleaned and recycled. The scrubber irrigation water removes particulate from the packed bed, and helps condense the nucleation water before it leaves the stack (Reference 39). The irrigation water cleanup system reduces the collected particulate to sludge. Approximately 60 lb/hr of sludge per test cell is produced when the scrubber is operating, and the sludge is approximately 25-percent solids. Because it is formed by coagulating particulate with calcium oxide (lime), the sludge is slightly toxic. However, it appears that the solid waste is a minor impact.

In controls using ferrocene fuel additive, some small amounts ferrocene could be introduced into the small amount of water discharge. Since ferrocene is only slightly toxic, no major water pollution problems are introduced, beyond those of the uncontrolled cells. Products of ferrocene combustion would be almost identical to fuel products, and therefore this impact is minimal.

Federal and state water regulations are concerned with discharges into navigable waterways. However, the water discharge from JETC's controlled or uncontrolled, is so minor that it cannot be classified as a regulated discharge.

4.4.3 People Impacts

Analyzing the impacts of JETC operations on the population is difficult. Potential impacts can be identified and discussed, but quantification of an impact is not straightforward. Keeping in mind that the same problem source will impact people differently, two possible impacts of jet engine test cell facilities are examined briefly below.

Visual

Uncontrolled JETCs show a visual plume during the average test. Complaints have been filed with BAAPCD regarding a visual impact upon the population in the area (Reference 58). Even if the test cell is controlled for particulate opacity, a steam plume will persist whenever quench water is being used. The color of this plume varies from white to black according to power, test cell and engine type, control method, and quench water flowrate.

Residents in the area have seen, and will continue to see, the steam plume from controlled or uncontrolled test cells. If they interpret the plume as a pollution source, then complaints will occur. By operating the JETC during evening or early morning hours, fewer people see the plume. However, the noise impact would be greater, and such scheduling may be impossible.

Noise

JETCs are a source of high sound levels relative to normal conversation and high levels may persist for several hours during a test. An estimate of sound levels at the perimeter of a base (where JETCs are located near the center of the base) can easily be made. As a general rule, sound drops by 6 dBA when distance from the sound source doubles. Using the JETC data in Reference 43 (90 dBA at 250 feet from the test cell), the sound level at the base perimeter (assumed to be 1000 yards) would be 70 dBA, or approximately speech level. From this exercise it can be concluded that if the JETCs do not directly border residential areas, the noise impact should be acceptable for daytime operation. Because the JETCs are located away from populated areas at the Alameda NARF (Reference 59), sound levels should be well below 70 dBA.

Aircraft Operations have more of an impact than JETCs. Noise complaints by Alameda residents originally directed at JETC operations, were found to be caused by night flights, not jet engine testing (Reference 60) Noise is an impact to which Alameda residents are sensitive but JETCs are not the source of the impact.

Using the scrubber will reduce noise levels further (Reference 43). clean combustor and ferrocene fuel additive will have or no impact on noise levels.

4.5 SUMMARY

This section summarizes the impact of uncontrolled and controlled JETC on the environment, and includes impacts on air, water, and people.

4.5.1 Uncontrolled JETC Emissions

On a source basis, worst-case Alameda JETC operations contribute very little (less than 0.26 percent) to the total nine county BAAPCD emissions (unburned hydrocarbons, carbon monoxide, nitrogen oxides, sulfur oxides, particulates) inventory. Alameda JETC operations also represent less than 11 percent of the emissions produced by military aircraft operations in the BAAPCD region. On an air quality basis, worst-case Alameda JETC operations contribute, at at most, 3 percent of particulates, 43 percent of unburned hydrocarbons, 0.3 percent of carbon monoxide, 6 percent of nitrogen oxides and 34 percent of sulfur oxides on a 24-hour comparison. Contibutions to the background levels are much less than these maximum values at other locations.

Comparing worst-case individual Alameda JETC emissions with the BAAPCD General Combustion Source Regulations, it is found that 40 percent of Alameda JETC operations exceed the opacity regulations.

4.5.2 Controlled JETC Emissions

The impact of wet packed scrubbers, clean combustors, and ferrocene fuel additive control strategies on JETC emissions has been assessed. Wet packed scrubbers reduce JETC plume opacities below RN 1, and reduce particulates 78 percent. Clean (smokeless) combustors also reduce plume opacities below RN 1, but reduce particulates 21 percent. Ferrocene fuel additive reduces plume opacity below RN 1 and reduces particulates by 53 percent. Gaseous emissions remain substantially unchanged with application of wet packed scrubbers and ferrocene fuel additive; the only change in gaseous emissions using clean combustors seems to be an increase in nitrogen oxides of roughly 50 percent.

Using these control strategies, the impact of JETC operations on ambient air quality is reduced in all respects except for NO_x. NO_x is increased by clean combustors. However, the increase is not large enough to alter the conclusion that JETCs contribute only minimally to the BAAPCD source inventory. Comparing controlled individual JETC emissions with

General Combustion Source Regulations for the BAAPCD indicates that all control stragegies will reduce the plume opacity below or near the RN 1 regulation. All control methods reduce particulate concentrations. Since uncontrolled concentrations are below regulations, controlled JETC particulate concentrations will be even further below the standards. Scrubber and additive control strategies do not alter JETC gaseous emissions sufficiently to alter the conclusion that gaseous emissions are below BAAPCD General Combustion Source Regulations. Application of clean combustors to the T56 engine may produce NO_x concentrations in excess of the regulation. It is estimated that 9 percent of Alameda JETC operations would exceed the NO_x regulation if clean combustors were applied to the T56 engine. Ferrocene added to the fuel is slightly toxic, but no more so than the fuel itself. When burned, ferrocene fuel additive yields primarily iron oxide, carbon dioxide, and water vapor. Taken alone, these substances are not very toxic; however, it has been suggested that synergistic reactions of iron oxide with combustion-produced POMs may produce carcinogens or transport them into the human body. Further study is required to prove or disprove this conjecture.

4.5.3 Impacts on Water and People

Controlled or uncontrolled JETCs have only minor water discharges which can be released onto the ground and evaporated. Discharge water might contain small amounts of degraded fuel and possibly ferrocene additive. The wet packed scrubber control method produces a solid cake (60-lbm/hr) waste from water treatment and recycling. Because of its lime content, this cake is slightly toxic.

Complaints of plume visibility have been received at the BAAPCD offices. These plumes are caused by both particulate matter and condensed water vapor. Since applying control methods will not reduce water condensation, some plume will always be present at high-power operation. However, control methods will reduce the opacity of the plume considerably.

Uncontrolled JETC operations are located sufficiently far away from civilian populations that their sound levels are not a nuisance. Wet packed scrubber controls can reduce these sound levels even futher.

SECTION 5

JET ENGINE TEST CELL EMISSIONS DATA

The general validity of published JETC data and measurement techniques was discussed in the Phase 1 study of JETC emissions (Reference 1). In this section, available plume opacity, gaseous and particulate emissions data for controlled and uncontrolled JETC are briefly described. Details of the (1) engine and test cell unit tested, (2) test method for opacity, particulates and gaseous emissions, (3) sampling locations, and (4) test cell conditions, as well as the detailed data are presented in Appendix B.

To characterize the environmental impact of controlled and uncontrolled JETC's, plume opacity, particulate and gaseous emission concentrations must be measured at the stack exit. These quantities vary as a function of engine type, power level and condition of the engine. Furthermore, the test cell itself affects emissions, according to the cell configuration, augmentor design and airflow, and quench water flow. Also, stack exit areas are typically large and test cell configurations generally create highly nonuniform distributions of stack exit velocity. Therefore, to characterize test cell emissions properly, extensive sampling must be conducted at the stack exit area for several test cell engine combinations.

Published JETC stack-exit emissions data are very sparse. They also are limited since only a few (or one) sampling points were measured for a large stack exit area. In addition, isokinetic particulate sampling rates

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have not been maintained in some cases, casting doubt on the reliability of the particulate data.

In the following paragraphs the JETC emissions data sources found during this study are briefly summarized. Comments on the reliability of the data are included here, and details of the data, including test conditions, are presented in Appendix B.

5.1 "NOISE AND AIR POLLUTION EMISSIONS FROM NOISE SUPPRESSORS FOR ENGINE TEST STANDS AND AIRCRAFT POWER CHECK PADS" (Reference 61)

This report presents gaseous and particulate emissions data taken on jet aircraft noise suppressors and a JETC. The noise suppressor data were obtained at McClellan (California) and Hill (Utah) Air Force Bases; the JETC data were obtained at McConnell (Kansas) Air Force Base. Based on multipoint CO_2 concentration measurements, a single stack exit sampling point was established at which "average" particulate and NO_x concentration data were collected. For particulate data, this "average" is somewhat suspect, since the distribution of velocity across the stack exit was highly nonuniform. Some areas even experienced negative velocities. Based on carbon and water balances, the overall accuracy of the multipoint gaseous data was estimated by the author to be between 1 and 52 percent. Because NO_x was sampled at a single point and only small particulate sample volumes were collected (4.1 to 13.65 cu ft), a much greater sampling error probably results for these data. Isokinetic sampling rates were maintained during particulate sampling.

Details of the data and the test conditions are given in Appendix B-1.

5.2 "PRELIMINARY REPORT: JET ENGINE TEST CELL EMISSIONS" (Reference 42)

The primary purpose of this study was to demonstrate the feasiblity of the JETC sampling procedure initiated at McClellan Air Force Base. Both gaseous and particulate data were obtained, however, the JETC stack exit was sampled at only a single point. Also, the J57 engine was only run at idle conditions during the sampling -- limiting the usefulness of the data in assessing the environmental impact of JETC's. The authors indicated that the NO_x concentration is probably low due to absorption in the sampling line and tedlar sampling bags.

Details of the data and the test conditions are given in Appendix B-2.

5.3 "TURBOJET AIRCRAFT ENGINE TEST CELL POLLUTION ABATEMENT STUDY" (Reference 62)

In this study, the test cell data from "Air Pollution Source Emissions Evaluation of Turbofan Jet Engine Test Facility at NAS, Albany, Georgia," Bibbens, R. N., et al., Report 64-037, May 1971, is presented. Emission levels were measured at the base of the stack for a J79 engine at power levels of idle, 95-percent thrust and afterburner. Stack exit particulate concentrations might be less than the measured values, due to particulate fallout within the stack. Since the original Albany NAS, report is not available, the reliability of the data cannot be determined at this time.

Details of the emissions data and test method are given in Appendix B-3.

5.4 "JET ENGINE TEST CELL TESI AUGMENTOR-SCRUBBER SYSTEM" (Reference 44)

This report presents the results of a study to determine how effectively the TESI wet packed nucleation scrubber (used at the Jacksonville NARF) reduced JETC particulate emissions and plume opacity. Three engines, (J52, J79 and TF30), were tested. The scrubber system was found to reduce plume opacity below Ringelmann 1 and grain loadings below or near 0.004 grains/cu ft. for all of the engines.

The opacity readings are probably accurate. However, it was noted in the report that the flow velocities at the scrubber face varied considerably and in some locations the velocity was so low that the direction of the flow could not be determined. Under these conditions, particulate sampling rates were probably not isokinetic. In addition, manifolding of sampling nozzles and lengthy sampling lines add uncertainty to the data. Because particulate data were inconclusive, a model scrubber was constructed and tested at Jacksonville NARF. The results of this model scrubber test are presented in Section 5.7 and Appendix B-6.

Details on the data taken in the TESI report and the test conditions are given in Appendix B-4.

5.5 "A SURVEY OF THE AIR POLLUTION POTENTIAL OF JET ENGINE TEST FACILITIES" (Reference 21)

In this report JETC plume opacities observed by Alameda Naval Air Rework Facility and BAAPCD personnel are presented. Data on seven engines (TF30-P-6 and P-8 (smokeless); J52-P-6A and P-8A (smokeless); J65 (clean); T56-A-10 and J57-P-8 are included, as shown in Figure 11. Within the bounds of uncertainty of the Ringelmann opacity measurement technique, the data appear to be valid. Also included in this report are J79 THC idle, and NO_x military power level data at the JETC stack exit, taken from the Naval Civil Engineering Laboratory Report No. 64-037, May 1971, Port Hueneme, California 94043. Since this report is not available, the reliability of the data and the measurement techniques cannot be determined. The quantitative values given were 105-ppm THC and 5-ppm NO_x. The NO_x data seem low when compared with USAF J79 stack measurements at McClellan Air Force Base (see Section 5.1).

5.6 "FERROCENE TEST FOR TEST CELL SMOKE ABATEMENT" (Reference 63)

This study investigated the feasibility of using a fuel additive to reduce test cell exhaust smoke to an acceptable level. Plume opacity readings for a J79 engine with and without ferrocene fuel additive were recorded at the North Island NARF. These results indicated that ferrocene is effective in keeping plume opacities below 20 percent at all power levels. Because the readings were taken on an overcast day, some uncertainty in the opacity levels may have resulted.

Details of the data and the test conditions are given in Appendix B-5.

5.7 "JET ENGINE TEST CELL POLLUTION ABATEMENT EFFICIENCY TESTS" (Reference 39)

This study reports the results of a test program to determine the effectiveness of a model wet packed crossflow scrubber in reducing JETC emissions. The study was prompted by the inconclusive data obtained on the full size scrubber at Jacksonville NARF. The test methods and data obtained during the study were judged by the EPA to be acceptable for determining scrubber effectiveness. J52 and J79 gaseous and particulate emissions data were obtained both upstream and downstream of the scrubber section. The model scrubber was located in an auxiliary ground-level duct and emission levels at the scrubber inlet may not be representative of stack exit values. However, the data should be useful in assessing the effectiveness of wet packed scrubbers in reducing JETC stack emissions.

Details of the data and the test conditions are given in Appendix B-6.

5.8 "A STUDY OF MEANS FOR ABATEMENT OF AIR POLLUTION CAUSED BY OPERATION OF JET ENGINE TEST FACILITIES" (Reference 37)

Included in this report are some gaseous emission test cell data obtained by the Navy. These data were extracted from "Pilot Tests for the

Establishment of an Environmental Data Base for Naval Aviation Activities," Osgood, F. B., et al., Naval Air Rework Facility, NAS, North Island, San Diego, California, August 1972. NO_x, THC and CO emissions from a J79 engine were measured at the base of a JETC stack over a wide range of power settings. Since the original report is not available, no comments on the reliability of the data or measurement techniques can be made. However, the emission levels are somewhat consistent with other JETC data.

The details of the data and measurement techniques are given in Appendix B-7.

5.9 **"RESULTS OF AIR SAMPLES FROM ELECTROSTATIC PRECIPITATOR"** (Reference 64)

This document presents a summary of the model electrostatic precipitator emissions data obtained by United Engineers and Constructors at the Jacksonville NARF. The format of the data is the same as that for the wet packed model scrubber.

Since the electrostatic precipitator and scrubber data were obtained on the same test cell and engine combination (see Section 5.7), these results can be compared directly. All tests were performed at normal rated power.

Since only a summary of the data is presented, it is not possible to comment on the reliability of the data. Although the data taken before the model electrostatic precipitator may not be representative of JETC stack exit values, the data are useful in assessing the effectiveness of electrostatic precipitators in reducing JETC emissions.

Details of the data and the test conditions are given in Appendix B-8.

5.10 **"PLUME OPACITY AND PARTICULATE EMISSIONS FROM A JET ENGINE TEST CELL"** (Reference 65)

The objective of this study was to determine the feasibility of utilizing optical transmissometers as mass emission monitors for JETCs.

JETC stack exit particulate emissions data as well as plume opacity measurements were obtained for J57 and J75 jet engines. The JETC used in the study is a reciprocating aircraft engine test cell which has been modified to test jet engines. The stack exit area is roughly three times larger than the largest test cell constructed for jet engine testing. Because of the large difference in exit areas, the emission rates and opacities determined in this study may not correspond with those obtained on more standard test cells.

The large stack areas of this cell also created some isokinetic sampling problems. Stack exit velocities during lower power operation were very low, and in some locations even negative. This made isokinetic particulate sampling very difficult at low power levels. Carbon dioxide concentration data indicated that the measured and actual velocities could be considerably different and even at higher power settings, velocity measurements were still somewhat uncertain. These problems could result in considerable errors in particulate mass concentration at low power settings.

Details of the data and the test conditions are given in Appendix B-9.

5.11 "GAS TURBINE ENGINE PARTICULATE MEASUREMENT TECHNIQUE, SUMMARY OF COORDINATING RESEARCH COUNCIL (CRC) PROGRAMS" (Reference 66)

One of the major objectives of this study was to identify changes in particulates between the rear engine face and the JETC stack exit. To meet this objective, particulates were sampled at both the engine exit and JETC stack exit, using both dry EPA and wet Los Angeles (LA) sampling techniques. Since the LA method catches condensed hydrocarbons as particulate, the LA method theoretically should yield higher particulate levels than the EPA method for the same engine conditions. This was not the case in this study. In addition, particulate data obtained by both the EPA and LA sampling trains lacked repeatability. Because of these problems, the data obtained in this study cannot be considered very reliable.

Details of the data and the test conditions can be found in Appendix B-10.

5.12 "AIRCRAFT ENGINE EMISSIONS CATALOG" (Reference 45)

Stack exit JETC particulate and gaseous emissions data for small turboshaft engines have been obtained at North Island NARF. An EPA Method 5 sampling train was used for particulate data. The repeatability of the data was not good. Data gathering time, which included two or three traverse points, was limited to 5 minutes at each power setting. Therefore, a great deal of confidence cannot be placed in the particulate data taken during this study.

Details of the data and the test conditions are given in Appendix B-11.

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APPENDIX A

SCRUBBER RETROFIT COST ESTIMATE

The following cost tables are extracted from the detailed Teller Environmental Systems, Incorporated scrubber cost estimate. The complete cost estimate is reproduced in the Phase 1 report (Reference 1).

ESTIMATED COST FOR A TELLER ENVIRONMENTAL SYSTEMS, INC.
EMISSION CONTROL SYSTEM
FOR
A STANDARD JET ENGINE TEST CELL
(J-79 ENGINE)

14 January 1976

by Charles B. Wyman

Denis R. J. Roy

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1. INTRODUCTION

The size of the Nucleation scrubber system is predicated on testing the J79 jet engine in its maximum afterburner mode (17,500-lbs. thrust). Also, the use of a TESI designed augmenter is assumed in order to reduce the amount of dilution air required.

Basis for the estimate is the prototype installation now operational at the Black Point test cell number one (1) NARF-JACKSONVILLE, FLORIDA. The estimate reflects refinements in material selection as well as improvements in design developed from operation of the prototype unit.

The cost per cell was established using the following assumptions:

1. A common cooling tower is to be used for two test cells.
2. The Cooling Tower is located between the two test cells (est. 200 ft. between cells).
3. One solids treatment system would be required for two test cells.
4. Structural design -- no snow loads incorporated.

The flow sheet attached is representative of typical flow conditions for gas and liquid streams.

SUMMARY OF COSTS

SECTION	TOTAL COST
TESI Augmenters	$ 36,600
Nucleation Systems	526,200
Cooling System	336,000
Solids Treatment System	179,500
Subtotal	$1,078,300
Contingency 10 Percent	108,000
Engineering and Royalty	225,000
TOTAL COST FOR INSTALLED SYSTEMS ON TWO JET ENGINE TEST CELLS	$1,411,300
EQUIVALENT COST PER TEST CELL	$ 705,650

BREAKDOWN OF COSTS FOR ONE TEST CELL

	(Prorated from Cost of Two cells)
Nucleation Scrubber	$ 167,600
TESI Augmentor	17,800
Cooling Tower	125,000
Solids Treatment System	50,600
Piping	70,500
Pumps	10,000
Instruments	19,900
Electrical	52,500
Miscellaneous	24,750
	538,650
10-Percent Contingency	54,500
	593,150
Engineering	112,500
	$ 705,650

APPENDIX B

JET ENGINE IN TEST CELL EMISSIONS DATA

B-1. DATA SUMMARY

Source: "Noise and Air Pollution Emissions from Noise Suppressors for Engine Test Stands and Aircraft Power Check Pads," Burnett, R. D., USAF Environmental Health Laboratory, Report 71M-19, McClellen Air Force Base, January 1972.

Unit Tested

Location:	McConnell AFB, KA	McClellan AFB, CA	Hill AFB, UT
Date Tested:	24-29 September 1971	7-11 September 1971	13-17 September 1971
Cell Type:	A/F 32T-2 cell	A/F 32A-13 supressor	A/F 32A-14 supressor
Stack Area:	242 sq ft	120 sq ft	120 sq ft
Stack Height:	~20 ft	~22 ft	~22 ft

Engine Tested

Unit:	TF30-P, J79-17	TF30 (F111A)	F4C
Duty Cycle:	Idle, military, afterburner	Military, afterburner	Idle, military, afterburner

Test Method

Particulates

Probe Type:	EPA Sampling Train
Method:	Wet — All condensibles at 70°F collected as particulate
Probe Location:	Stack exit
Number of Points:	One "average" point
Volume Sampling Rate:	5.1-13.7 scf dry
Isokinetic:	0.75-1.03
Opacity Measurement:	Ringelmann
Opacity Type:	Idle RN < 1, military RN ~ 1, afterburner — water plume

Gaseous Laboratory Analysis

Probe Type:	Stainless steel
NO_x	Phenol disulfonic acid method
CO	Nondispersive infrared analyzer
UHC	Gas chromatographic

Emissions Data

Table B-1

TABLE B-1. DATA SUMMARY SHEET

	F-111A	TF-30	F-4C	J-79
Stack Gas Flow				
Idle				
Total (dry scfm)	278000	178000	135000	102000
scfm/1000 lbs fuel	139000	178000	67500	96000
Military				
Total (dry scfm)	550000	471000	339000	449000
scfm/1000 lbs fuel	68700	70000	40900	52400
Afterburner (Zone 3)				
Total (dry scfm)	500000	505000	----	----
scfm/1000 lbs fuel	21500	28200	----	----
Max. Afterburner				
Total (dry scfm)	480000	435000	318000	482000
scfm/1000 lbs fuel	12200	10200	10700	15800
Particulate Emissions (lb/1000 lbs fuel)				
Idle	26.5*	26.5	72.4	32.4
Military	8.34	23.7	4.32	12.8
Afterburner (Zone 3)	13.3	11.9	----	----
Max. Afterburner	29.3	5.36	10.8	7.18

* TF-30 data - no idle data taken during F-111A test

TABLE B-1. Continued

	F-111A	TF-30	F-4C	J-79
Nitrogen Oxide Emissions, as NO_2 (lb/1000 lbs fuel)				
Idle	6.52*	6.52	6.75	5.14
Military	26.9	19.7	12.7	13.8
Afterburner (Zone 3)	9.62	7.38	----	----
Max. Afterburner	9.0	4.47	8.6	5.08
Carbon Monoxide Emissions (lb/1000 lbs fuel)				
Idle	81.4	46.4	NM	62.5
Military	4.39	<3.04	NM	2.73
Afterburner (Zone 3)	40.6	52.1	NM	----
Max. Afterburner	6.39	24.8	NM	31.9
Ethylene Emissions (lb/1000 lbs fuel)				
Idle	3.62	3.09	NM	2.07
Military	0.165	<0.30	NM	<0.23
Afterburner (Zone 3)	1.0	2.70	NM	----
Max. Afterburner	0.014	<1.89	NM	<0.068
Gaseous Hydrocarbons, as Hexane (lb/1000 lbs fuel)				
Idle	15.8	9.49	NM	12.8
Military	Nil	0.934	NM	1.4
Afterburner (Zone 3)	2.58	7.91	NM	----
Max. Afterburner	Nil	0.14	NM	1.34

* TF-30 data - no idle data taken during F-111A test

TABLE B-1. Concluded

	F-111A	TF-30	F-4C	J-79
Average Condensate Concentrations (mg/liter condensate)				
Formaldehyde	45-73	9.5	20-40	37.8
Nitrates	24-44	23.0	3-40	31.0
Nitrites	3	1.0	----	1.1
Heavy Oils	10	6.9	----	12.1
Fuel Consumption (1000 lbs/hr)				
Idle	1.0-1.5	0.999-1.5	1.0	1.062-1.075
Military	6.8-7.01	6.725-7.53	7.2	8.370-8.574
Afterburner (Zone 3)	22.0-22.3	17.89-21.01	----	----
Max. Afterburner	37.2-38.4	42.59-43.12	28.8	30.5-30.6

B-2. DATA SUMMARY

Source: "Preliminary Report: Jet Engine Test Cell Emissions," Burnett, R. D., USAF Environmental Health Laboratory Report 70M-37, McClellan Air Force Base, California, December 1970.

Unit Tested

Location:	McClellan Air Force Base
Date Tested:	17 November 1970
Cell Type:	Type A
Stack Area:	253 sq ft

Engine Tested

Unit:	J57 engine
Duty Cycle:	Idle only
Fuel Rate:	1000 lbm/hr

Test Method

Particulate:

Probe Type	Stainless steel probe
Method	In situ fiberglass filter, dry catch
Probe Location	Near stack wall at exit
Number of Points	One sampling point
Isokinetic	0.95

Gaseous Laboratory Analysis

Probe Type

NO_x	Phenol disulfonic acid method
CO	Infrared
UHC	Flame ionization; gas chromatography

Emissions Data

TEST CELL EMISSIONS (J57 ENGINE AT IDLE)

	PPM	lbs/hr and lbs/1000 lbs fuel*
Carbon Dioxide	2,550	--
Carbon Monoxide	66	116.5
Oxides of Nitrogen (as NO_2)**	1.0	2.9
Total Hydrocarbons (as C atoms)	60	45.4
Paraffins (as C atoms)	24	18.1
Aromatics (as C atoms)	10	7.6
Olefins (as C atoms)	24.4	18.5
Acetylene (as C atoms)	1.6	1.2
Particulates (95% Isokinetic)	--	2.07

* Fuel rate = 1000 lbs/hr, thus emissions in lbs/hr = lbs/1000 lbs fuel

** Collected in Tedlar bag at the end of the sampling train thus an undetermined quantity of NO_x was lost in the sample line and bag.

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B-3. DATA SUMMARY

Source: "Turbojet Aircraft Engine Test Cell Pollution Abatement Study," Naval Facilities Engineering Command, Naval Civil Engineering Laboratory Report CR74.001, June 1975. Data presented extracted from "Air Pollution Source Emissions Evaluation of Turbofan Jet Engine Test Facility At NAS, Albany, Georgia," Bibbens, R. N., et al., Report 64-037, May 1971.

Unit Tested

Location	NAS, Albany, Georgia
Date Tested	1971
Cell Type	Type A
Stack Area	138 sq ft

Engine Tested

Unit	J79
Duty Cycle	Idle, 95 percent thrust, afterburner

Emissions Data	Table B-2

B-4. DATA SUMMARY

Source: "Jet Engine Test Cell TESI Augmentor-Scrubber System," Teller Environmental Systems, Inc., Final Report, December 1971.

Unit Tested

Location	NARF – JAX, Black Point Test Cell No. 1
Date Tested:	December 1970 through May 1971
Cell Type	Type A
Stack Area	Scrubber face area, 960 sq ft
Pollution Control Equipment	Prototype scrubber and augmentation system mounted on exhaust stack of cell

Engine Tested

Unit	J79, TF30, J52
Duty Cycle	Idle, normal, military

Test Method

Particulates	
Probe Type	Impingers, filters connected to fixed manifold at stack exit
Probe Location	Scrubber face
Number of Points	Six test points
Volume Sampling Rate	11.5 to 26 liters/min
Isokinetic	Attempted
Opacity Measurement Type	Ringelmann

Emissions Data	Tables B-3, B-4, B-5

TABLE B-2. ALBANY, GEORGIA J79 TEST (A)

MODE	FUEL LB/HR	STACK SCFM	PARTICULATES LB/HR	PARTICULATES GR/SCF	PARTICULATES WT % <1.5 MICRON	RINGEL-MANN NUMBER	NO2 LB/HR	NO2 VOL PPM	SO2 VOL PPM	CO VOL. PPM	HYDROCARBONS(2) LB/HR	HYDROCARBONS(2) VOL PPM	ETHYLENE LB/HR	ETHYLENE PPM	TEMP °F	STACK VELOCITY(3) FT/SEC	JET ENGINE RPM
IDLE	525	124,120	22	0.021	20	0.5	-	2	0	165	-	30	-	-	180	12.5	5,083
95% THRUST	8,940	521,020	70	0.016	75	2.0	-	0.3	0	13	-	1.5	-	-	310	63.1	7,358
AFTERBURNER(1)	30,270	687,590	97	0.016	50	1.0	-	7	15	270	-	13	-	-	338	83.8	7,420

(1) WITH 500 GPM QUENCH WATER
(2) AS HEXANE
(3) STACK 20 X 20 FEET
(4) NOT COUNTING SOLIDS IN QUENCH WATER

(A) AIR POLLUTION SOURCE EMISSIONS OF TURBOFAN JET ENGINE TEST FACILITY AT NAS, ALBANY, GEORGIA, REPORT 64-037, MAY 1971 BY R N BIBBENS, J C KING AND W W WATSON

TABLE B-3. PARTICULATE EMISSIONS FROM JET ENGINES IN TEST CELL INLET TO CONTROL SYSTEM

		EMISSIONS - GRAINS/SCF			
ENGINE	**MODE**	**ENV/ONE-1**	**NARF**	**ENV/ONE-2(3)**	Based on Solids Collected in Scrubber Water,(1,2) (Does not include drain)
J-79	IDLE	0.0092		0.0153	0.0029
	NORMAL			0.0234	0.0131
	MILITARY	0.021	0.0348	0.0388	0.065
	AB	0.059		Questionable	0.08
J-52	IDLE	0.0034		0.0044	
	NORMAL			0.0157	
	MILITARY	0.0059	0.0128	0.0088	0.041
TF-30	IDLE			0.0079	0.006
	NORMAL			0.0079	0.0083
	MILITARY		0.0054	0.0096	0.054

Key:

1 - Gas flow on which loading is based:

J-79	Mil	320,000	scfm	TABLE 7-1
J-79	A/B	260,000	scfm	TABLE 7-1
J-79	Normal	300,000	scfm	Assumed
J-79	Idle	200,000	scfm	Assumed
TF-30	Mil	350,000	scfm	TABLE 7-1
TF-30	Normal	300,000	scfm	Assumed
TF-30	Idle	200,000	scfm	Assumed
J-52	Mil	350,000	scfm	Assumed
J-52	Normal	300,000	scfm	Assumed
	Idle	200,000	scfm	Assumed

2 - Solids collected at base of stack were not measured.

3 - A portion of the particulates were collected prior to this sample because of condensation in the stack and the internal section of the scrubber. This is evident from the total black coating of the internals.

TABLE B-4. DETAILED SAMPLE LEVELS AT OUTLET OF CONTROL SYSTEM

	Point	Mass collected grams	Velocity (fps)	Temperature °F
J-79 Normal	1	.0030	120	400
Time Sampled	2	.0024	230	400
5 min.	3	.0014	60	400
	4	.0019	226	400
	5	.0022	>260	400
	6	.0029	165	400
				(Reported)
Min. AB	1	.0029	130	345
Time Sampled	2	.0038	260	410
4 min.	3	.0022	98	320
	4	.0033	165	410
	5	.0025	>260	320
	6	.0033	184	345
Max. AB	1	.0066	163	375
Time Sampled	2	.0035	>260	375
4 min.	3	.0045	105	375
	4	.0049	165	375
	5	.0066	>260	375
	6	.0053	165	375

TABLE B-5. EMISSION LEVELS FROM TESI CONTROL SYSTEM

ENGINE	MODE	PARTICULATE EMISSIONS Grains/cu.ft.	RINGLEMAN	
J-79	Idle	0.0024	Less than 1/2	
	Normal	0.0029	" " "	
	Military	0.0024	" " "	
TF-30	Idle	0.0019	" " "	
	Normal	0.0014	" " "	
	Military	0.0018	" " "	
J-79	Idle	0.0052	" " "	These tests
	Normal	0.0029	" " "	are questio
	Military	0.0062	" " "	<ed by ENVIR
	Max. A/B	0.0033	" " "	MENT/ONE.

B-5. DATA SUMMARY

Source: "Ferrocene Test for Test Cell Smoke Abatement," Naval Air Propulsion Test Center, NAVAIRSYS COMREPAC Project Order No. P.O. 3-0124, February 1975.

Unit Tested

Location: North Island NARF, San Diego, CA

Cell Type: Type A

Pollution Control Equipment: Ferrocene fuel additive

Engine Tested

Unit: J79

Duty Cycle: Idle, military, afterburner

Test Method

Opacity Measurement Type: Visual Opacity

Emissions Data

NORTH ISLAND J79 FERROCENE TEST

Power Condition	Visual Opacity Without Ferrocene	Additive Concentration, % By Weight	Visual Opacity* With Ferrocene
Idle	5%	-	-
85% Military	30%	.05	20%
Military	50%	.04	20%
A/B Minimum (1)	15%	-	-
A/B Maximum (2)	20%	-	-

(1) Black and White (steam) plume.

(2) Steam plume.

* These readings made on overcast day.

B-6. DATA SUMMARY

Source: "JETC Pollution Abatement Efficiency Tests," Jacksonville Naval Air Rework Facility Report, March 1973 - May 1974.

Unit Tested

Location:	JAX NARF, Black Point No. 1, Model Scrubber
Date Tested:	May 1963 - February 1974
Cell Type:	Permanent, concrete
Stack Area:	Model scrubber, 16 ft^2 at sampling positions 1 and 2
Stack Velocity:	600-750 ft/min at position 1 and 400-630 ft/min at position 2
Stack Temperature:	-135 average
Water Consumption:	Quench water = 700 gal/min
Pollution Control Equipment:	Model scrubber designed by Plant Engineering Division and Materials Engineering Division

Test Method

Particulates

Probe Type:	Research appliance
Method:	Method 5, no cyclones, probe washed and residue collected
Probe Location:	Up and downstream of scrubber
Number of Points:	25 points x 5 min/point
Volume Sampling Rate:	125 min sampling 0.5-inch probe nozzle
Isokinetic:	Yes
Opacity Measurement Type	None

Gaseous

Probe Type

NO_x	Chemiluminescence
SO_x	None
CO	Nondispersive infrared
UHC	Flame ionization
CO_2	Nondispersive infrared

Turbidity of sump water was checked to determine amount of suspended particulate.

Engine Tested

Unit	J52-P8B		J79-10			
	NR	MIL	NR	MIL	MIN AB	MAX AB
Power, thrust lbf	7800	8300	7500	11000	13000	16000
Fuel rate, lbs/hr	5600	6800	5400	9500	17000	32500
Quench water, gpm	700	700	700	700	1000	1000

Emissions Data Tables B-6 through B-17

TABLE B-6. SUMMARY OF EMISSIONS FROM AN EXPERIMENTAL MODEL WET SCRUBBER AT JACKSONVILLE NAVAL AIR STATION

Cycle	Date 1973	Engine[a] Type	RPM[b]	Thrust[b] lbs.	Fuel Flow[b] lbs/hr	Engine Exhaust Temperature[b] °F	Emissions, Average Values: CO[c] ppm Probe 1[f]	CO[c] ppm Probe 2	CO$_2$ % Probe 1	CO$_2$ % Probe 2	NO ppm Probe 1	NO ppm Probe 2	NO$_x$ ppm Probe 1	NO$_x$ ppm Probe 2	Packing[d] Size 2"	Packing width 1'
1	23 May	J52	11708	7890	6520	1100	32.6	32.6	1.65	1.59	51.3	50.2	53.1	51.2	0	0
2	25 May (1)	J52	11653	7790	6360	1078	35.5	35.1	1.69	1.65	48.1	46.9	50.0	47.7	0	0
3	25 May (2)	J52	11759	7832	6470	1109	43.5	43.1	1.70	1.66	53.1	51.9	54.8	51.8	0	0
4	26 May (1)	J52	11669	7750	6310	1081	36.0	35.5	1.64	1.58	52.0	51.5	52.5	51.8	0	0
5	26 May (2)	J52	11728	7720	6330	1099	35.6	35.1	1.66	1.63	53.8	53.6	55.0	53.5	1	1
6	28 May (1)	J52	11588	7860	6590	1110	34.0	34.7	1.73	1.72	50.5	50.0	52.1	51.9	1	1
7	28 May (2)	J52	11913	2800	6650	1135	30.0	30.0	1.65	1.64	56.0	56.5	56.5	56.5	1	1
8	29 May	J52	11728	7778	6430	1100	35.3	33.6	1.69	1.67	48.6	48.3	49.8	49.5	1	1
9	30 May	J52	11655	7720	6340	1085	29.4	29.6	1.63	1.60	53.6	52.7	54.0	53.6	1	1
10	31 May (1)	J52	11574	7786	6330	1070	31.5	33.0	1.60	1.59	53.7	53.5	54.5	54.8	1	1
11	31 May (2)	J52	11732	7668	6310	1100	29.6	29.2	1.62	1.58	56.3	56.5	60.0	59.0	2	1
12	1 June (1)	J52	--	7750	6410	1091	29.8	30.0	1.66	1.62	51.3	51.3	53.3	53.2	2	1
13	1 June (2)	J52	11750	7634	6360	1110	26.9	26.5	1.63	1.60	56.7	55.3	57.0	56.0	2	1
14	4 June (1)	J52	11710	7828	6450	1095	30.0	30.2[e]	1.65	1.55[e]	54.3	51.3[e]	57.0	54.0[e]	2	1
15	4 June (2)	J52	11725	7842	6410	1105	29.4	29.8[e]	1.60	1.56[e]	54.8	53.5[e]	55.0	53.0[e]	2	1
16	5 June (1)	J52	11662	7730	6380	1085	33.0	31.8	1.65	1.62	52.5	54.0	54.5	55.5	2	1
17	5 June (2)	J52	11742	7776	6470	1110	34.8	34.2	1.63	1.61	53.6	54.3	56.3	55.8	3	1
18	6 June	J52	11698	7724	6400	1090	30.5	30.0	1.65	1.63	53.9	53.5	57.0	56.0	3	
19	13 June	J79	6977	6698	5516	892	40.1	39.8	1.54	1.53	25.0	25.5	26.5	27.1	3	
20	14 June	J79	6974	6948	5700	892	43.8	43.8	1.53	1.52	25.9	26.3	26.6	27.4	3	

[a] J52-P8 S/N 677211 or J79-10 S/N 448 425 [b] Observed values. [c] This value has not been corrected for the interference of water and carbon dioxide. [d] "Tellerettes". [e] Probe positi

[f] 1 denotes upstream, 2 downstream of scrubber.

TABLE B-7. J-79 ENGINE DATA USING TELLERETTES

	INLET	OUTLET	INLET	OUTLET	INLET	OUTLET
Date	11-8	11-8	11-9	11-9	11-12	11-12
No. ft. of packing	4		4		4	
Engine operating condition	NR		Mil		Mil	
Flow at #1 Sump gal./min.	15.2		10.9		10.1	
Flow at #2 Sump gal./min.	86.3		84.6		85.6	
Vol. of dry gas sampled, SCF	87.87	76.77	87.79	70.80	92.43	72.78
Stack flow rate, SCFM, dry	8878.8	7356.4	7998.3	6545.8	8580.8	6689.3
Stack gas velocity, at stack conditions, f.p.m.	741.1	547.4	730.2	516.8	767.8	519.6
Moisture, % by volume	17.5	10.4	23.0	13.6	22.2	13.2
Stack gas temp. degree F.	129.8	110.8	140.0	121.6	139.8	120.2
Isokinetic, %	92.6	97.6	102.6	101.2	100.7	101.7
Particulate Results						
(a) Probe and filter catch Grains/SCF, dry, x 10-3	7.18	3.14	5.54	3.83	7.10	3.75
(b) Total Catch Grains/SCF, dry, x 10-3	8.15	3.99	5.65	4.96	9.88	4.57
(c) Particulates from #1 Sump Water sample grains/SCF, x 10-3	8.20		7.19		10.31	
Particulate Removal Efficiency						
Based on air sample (a), %	56.3		30.9		58.8	
Based on air sample (b), %	51.0		12.2		53.7	
Based on total (air and water, a+c), %	79.6		69.9		80.7	
Based on total (air and water, b+c), %	75.6		61.4		77.4	
Entrained Water Removal, %	57.2		61.0		58.3	

TABLE B-8. J-79 ENGINE DATA USING TELERETTES

	INLET	OUTLET	INLET	OUTLET	INLET	OUTLET
Date	11-15	11-15	11-16	11-16	11-19	11-19
No. ft. of packing	5		5		5	
Engine operating condition	NR		NR		NR	
Flow at #1 Sump gal./min.	12.3		12.4		13.2	
Flow at #2 Sump gal./min.	86.0		86.0		3.0	
Vol. of dry gas sampled, SCF	72.19	59.92	74.60	61.01	72.70	67.20
Stack flow rate, SCFM, dry	6980.43	5409.81	7028.6	5619.6	6935.4	5745.2
Stack gas velocity, at stack conditions, f.p.m.	584.7	392.5	599.5	406.9	577.3	465.9
Moisture, % by volume	17.8	8.8	18.8	8.3	17.1	15.2
Stack gas temp. degree F.	129.0	105.0	130.0	104.6	128.8	126.0
Isokinetic, %	96.7	103.6	99.3	101.5	99.0	109.4
Particulate Results						
(a) Probe and filter catch Grains/SCF, dry, x 10-3	7.62	2.57	7.27	3.48	7.37	2.68
(b) Total Catch Grains/SCF, dry, x 10^{-3}	7.66	2.85	7.62	3.48	8.03	2.80
(c) Particulates from #1 Sump Water sample grains/SCF, x 10^{-3}	9.53		11.02		12.34	
Particulate Removal Efficiency						
Based on air sample (a), %	66.3		52.1		63.6	
Based on air sample (b), %	62.8		54.3		65.2	
Based on total (air and water, a+c), %	85.0		81.0		86.4	
Based on total (air and water, b+c), %	83.4		81.3		86.3	
Entrained Water Removal, %	68.3		78.6		23.6	

TABLE B-9. J-79 ENGINE DATA USING TELLERETTES

	INLET	OUTLET	INLET	OUTLET	INLET	OUTLET
Date	11-26	11-26	12-4	12-4	12-5	12-5
No. ft. of packing	5		5		5	
Engine operating condition	NR		Mil		Mil	
Flow at #1 Sump gal./min.	13.2		9.6		9.5	
Flow at #2 Sump gal./min.	.9		86.4		89.8	
Vol. of dry gas sampled, SCF	73.07	63.84	90.05	72.94	86.44	71.09
Stack flow rate, SCFM, dry	6978.3	5426.6	8031.1	6463.6	7707.9	6224.3
Stack gas velocity, at stack conditions, f.p.m.	586.2	443.4	732.0	499.6	705.7	485.3
Moisture, % by volume	17.7	15.4	22.8	12.3	22.9	12.6
Stack gas temp. degree F.	130.4	129.2	141.3	118.0	141.2	119.0
Isokinetic, %	97.9	110.0	104.9	105.5	104.9	106.8
Particulate Results						
(a) Probe and filter catch Grains/SCF, dry, x 10-3	8.56	3.26	8.57	4.37	9.50	3.92
(b) Total Catch Grains/SCF, dry, x 10^{-3}	8.56	3.26	8.57	4.37	9.71	4.53
(c) Particulates from #1 Sump Water sample grains/SCF, x 10-3	14.58		12.73		13.07	
Particulate Removal Efficiency						
Based on air sample (a), %	62.0		49.0		58.7	
Based on air sample (b), %	62.0		49.0		53.4	
Based on total (air and water, a+c), %	85.9		79.5		82.6	
Based on total (air and water, b+c), %	85.9		79.5		80.1	
Entrained Water Removal, %	36.9		65.6		64.7	

TABLE B-10. J-79 ENGINE DATA USING HEILE PACKING

	INLET	OUTLET	INLET	OUTLET	INLET	OUTLET
Date	1-30	1-30	1-31	1-31	2-1 AM	2-1 AM
No. ft. of packing	3		3		3	
Engine operating condition	NR		NR		NR	
Flow at #1 Sump gal./min.	12.3		16.2		14.7	
Flow at #2 Sump gal./min.	.2		.5		75.0	
Vol. of dry gas sampled, SCF	73.04	62.75	91.46	85.15	91.89	75.01
Stack flow rate, SCFM, dry	6539.8	5448.0	8919.5	8075.4	9046.4	7510.6
Stack gas velocity, at stack conditions, f.p.m.	542.4	437.1	746.1	638.8	760.4	566.4
Moisture, % by volume	16.6	14.1	17.4	12.9	17.7	10.8
Stack gas temp. degree F.	129.6	126.8	130.2	127.6	131.0	115.4
Isokinetic, %	104.4	107.7	95.9	98.60	95.0	93.4
Particulate Results						
(a) Probe and filter catch Grains/SCF, dry, x 10-3	6.90	3.09	6.67	2.53	6.55	3.20
(b) Total Catch Grains/SCF, dry, x 10-3	7.27	3.41	6.85	2.68	7.06	3.74
(c) Particulates from #1 Sump Water sample grains/SCF, x 10-3	10.69		9.33		9.30	
Particulate Removal Efficiency						
Based on air sample (a), %	55.2		62.0		51.2	
Based on air sample (b), %	53.1		60.9		47.0	
Based on total (air and water, a+c), %	82.4		84.2		79.8	
Based on total (air and water, b+c), %	81.0		83.5		77.2	
Entrained Water Removal, %	42.5		75.3		67.0	

TABLE B-11. J-79 ENGINE DATA USING HEILE PACKING

	INLET	OUTLET	INLET	OUTLET	INLET	OUTLET
Date	2-1	2-1	2-5	2-5	2-7	2-7
No. ft. of packing	3		3		5	
Engine operating condition	NR		NR		NR	
Flow at #1 Sump gal./min.	15.1		18.		13.3	
Flow at #2 Sump gal./min.	72.0		1.0		80.5	
Vol. of dry gas sampled, SCF	85.89	77.46	71.36	64.98	93.94	82.06
Stack flow rate, SCFM, dry	8851.3	7760.1	12014.7	11295.1	9297.3	7562.0
Stack gas velocity, at stack conditions, f.p.m.	738.1	581.9	980.4	890.3	771.3	562.5
Moisture, % by volume	17.3	10.3	16.3	13.3	16.9	8.9
Stack gas temp. degree F.	129.8	114.2	126.0	125.4	126.6	115.2
Isokinetic, %	90.7	93.3	98.8	95.7	94.5	101.5
Particulate Results						
(a) Probe and filter catch Grains/SCF, dry, x 10-3	6.46	3.22	8.81	6.00	6.71	2.80
(b) Total Catch Grains/SCF, dry, x 10-3	7.21	3.66	9.67	6.66	7.31	3.17
(c) Particulates from #1 Sump Water sample grains/SCF, x 10-3	8.86		8.84		7.35	
Particulate Removal Efficiency						
Based on air sample (a), %	50.1		31.9		58.3	
Based on air sample (b), %	49.3		31.1		56.6	
Based on total (air and water, a+c), %	79.0		66.0		80.1	
Based on total (air and water, b+c), %	77.2		64.0		78.4	
Entrained Water Removal, %	65.9		54.5		94.0	

TABLE B-12. J-79 ENGINE DATA USING HEILE PACKING

	INLET	OUTLET	INLET	OUTLET	INLET	OUTLET
Date	2-8	2-8	2-11	2-11		
No. ft. of packing	5		5			
Engine operating condition	NR		NR			
Flow at #1 Sump gal./min.	14.2		13.9			
Flow at #2 Sump gal./min.	.5		.6			
Vol. of dry gas sampled, SCF	91.30	86.02	95.32	85.88		
Stack flow rate, SCFM, dry	9348.9	8041.2	9425.2	8072.5		
Stack gas velocity, at stack conditions, f.p.m.	772.9	643.4	757.9	632.5		
Moisture, % by volume	16.4	13.8	15.1	13.0		
Stack gas temp. degree F.	127.6	125.	125.0	122.8		
Isokinetic, %	91.3	100.0	94.6	99.5		
Particulate Results						
(a) Probe and filter catch Grains/SCF, dry, x 10-3	5.46	3.08	8.74	2.90		
(b) Total Catch Grains/SCF, dry, x 10-3	5.81	3.11	9.13	3.39		
(c) Particulates from #1 Sump Water sample grains/SCF, x 10-3	8.60		7.84			
Particulate Removal Efficiency						
Based on air sample (a), %	43.7		66.8			
Based on air sample (b), %	46.5		62.9			
Based on total (air and water, a+c), %	78.1		82.5			
Based on total (air and water, b+c), %	78.4		80.0			
Entrained Water Removal, %	39.7		37.8			

TABLE B-13. J-52 ENGINE DATA USING TELLERETTES

	INLET	OUTLET	INLET	OUTLET	INLET	OUTLET
Date	12-7	12-7	12-11 AM	12-11 AM	12-11 PM	12-11 PM
No. ft. of packing	5		5		5	
Engine operating condition	NR		NR		NR	
Flow at #1 Sump gal./min.	16.4		15.3		16.4	
Flow at #2 Sump gal./min.	79.0		85.0		1.0	
Vol. of dry gas sampled, SCF	79.54	68.66	98.28	75.35	86.86	72.49
Stack flow rate, SCFM, dry	7830.0	6077.5	8580.1	7340.7	8115.2	6722.3
Stack gas velocity, at stack conditions, f.p.m.	638.0	431.1	682.6	508.7	650.9/	524.5
Moisture, % by volume	16.4	7.7	14.5	6.5	15.0	12.9
Stack gas temp. degree F.	125.2	101.0	123.0	95.6	124.4	123.0
Isokinetic, %	95.0	105.6	107.1	96.0	100.1	100.8
Particulate Results						
(a) Probe and filter catch Grains/SCF, dry, x 10-3	10.46	4.17	7.35	2.33	6.24	3.04
(b) Total Catch Grains/SCF, dry, x 10-3	10.88	4.24	7.91	2.86	6.49	3.29
(c) Particulates from #1 Sump Water sample grains/SCF, x 10-3	1.59		1.64		1.81	
Particulate Removal Efficiency						
Based on air sample (a), %	60.1		68.3		51.3	
Based on air sample (b), %	61.0		63.8		49.3	
Based on total (air and water, a+c), %	65.4		74.1		62.2	
Based on total (air and water, b+c), %	66.0		70.0		60.3	
Entrained Water Removal, %	72.4		74.4		43.5	

TABLE B-14. J-52 ENGINE DATA USING TELLERETTES

	INLET	OUTLET	INLET	OUTLET	INLET	OUTLET
Date	1-2 AM	1-2 AM	1-2 PM	1-2 PM	2-15 AM	2-15 AM
No. ft. of packing	5		5		5	
Engine operating condition	NR		Mil		NR	
Flow at #1 Sump gal./min.	17.6		15.8		15.7	
Flow at #2 Sump gal./min.	1.0		79.0		71.0	
Vol. of dry gas sampled, SCF	85.64	71.57	93.76	80.32	94.93	88.50
Stack flow rate, SCFM, dry	8684.5	6495.3	9262.6	7547.1	9318.4	8232.6
Stack gas velocity, at stack conditions, f.p.m.	725.6	519.6	797.5	560.3	771.3	611.5
Moisture, % by volume	18.0	14.7	19.8	10.1	16.4	9.5
Stack gas temp. degree F.	129.6	126.2	134.6	113.6	130.6	112.4
Isokinetic, %	92.2	103.0	94.7	99.5	95.3	100.5
Particulate Results						
(a) Probe and filter catch Grains/SCF, dry, x 10-3	6.37	3.44	7.62	2.78	6.42	3.86
(b) Total Catch Grains/SCF, dry, x 10^{-3}	7.09	3.55	8.01	3.22	6.73	4.32
(c) Particulates from #1 Sump Water sample grains/SCF, x 10^{-3}	1.50		2.12		1.77	
Particulate Removal Efficiency						
Based on air sample (a), %	46.0		63.5		39.9	
Based on air sample (b), %	49.9		59.8		35.9	
Based on total (air and water, a+c), %	56.3		71.5		52.9	
Based on total (air and water, b+c), %	58.7		68.2		49.3	
Entrained Water Removal, %	40.9		75.9		64.7	

TABLE B-15. J-52 ENGINE DATA USING TELLERETTES

	INLET	OUTLET	INLET	OUTLET	INLET	OUTLET
Date	2-20 PM	2-20 PM	2-15 PM	2-15 PM	2-20 AM	2-20 AM
No. ft. of packing	3		3		3	
Engine operating condition	NR		NR		NR	
Flow at #1 Sump gal./min.	14.2		16.7		15.1	
Flow at #2 Sump gal./min.	80.0		.6		.6	
Vol. of dry gas sampled, SCF	86.26	80.75	96.69	85.99	95.90	86.38
Stack flow rate, SCFM, dry	9297.9	7680.3	8927.2	7601.7	9295.4	7938.0
Stack gas velocity, at stack conditions, f.p.m.	775.5	565.9	749.3	615.7	774.8	637.7
Moisture, % by volume	17.1	9.1	17.3	14.8	17.0	14.4
Stack gas temp. degree F.	129.6	110.0	131.6	128.0	128.0	123.8
Isokinetic, %	86.8	98.3	101.3	105.8	96.5	101.8
Particulate Results						
(a) Probe and filter catch Grains/SCF, dry, x 10-3	8.12	3.99	7.39	3.15	7.84	4.60
(b) Total Catch Grains/SCF, dry, x 10^{-3}	9.16	5.36	7.84	3.74	8.40	5.51
(c) Particulates from #1 Sump Water sample grains/SCF, x 10^{-3}	1.61		1.53		1.44	
Particulate Removal Efficiency						
Based on air sample (a), %	50.9		57.4		41.3	
Based on air sample (b), %	41.5		52.3		34.4	
Based on total (air and water, a+c), %	59.0		64.7		50.4	
Based on total (air and water, b+c), %	50.2		60.1		44.0	
Entrained Water Removal, %	72.5		34.6		32.0	

TABLE B-16. J-52 ENGINE DATA USING HEILE PACKING

	INLET	OUTLET	INLET	OUTLET	INLET	OUTLET
Date	1-8 AM	1-8 AM	1-8 PM	1-8 PM	1-11	1-11
No. ft. of packing	Demist		Demist		3	
Engine operating condition	NR		NR		NR	
Flow at #1 Sump gal./min.	17.8		17.8		17.5	
Flow at #2 Sump gal./min.	.4		.4		.4	
Vol. of dry gas sampled, SCF	84.43	72.44	79.62	71.44	79.60	72.71
Stack flow rate, SCFM, dry	8225.2	6717.7	8178.7	6693.7	7496.3	6597.1
Stack gas velocity, at stack conditions, f.p.m.	660.1	527.4	668.6	531.3	628.8	532.8
Moisture, % by volume	14.7	13.0	16.1	13.9	17.7	14.7
Stack gas temp. degree F.	125.5	123.8	127.8	125.4	130.6	124.4
Isokinetic, %	96.0	100.8	91.0	99.8	99.3	10[illegible]
Particulate Results						
(a) Probe and filter catch Grains/SCF, dry, x 10-3	4.80	2.62	5.55	3.21	5.03	3.14
(b) Total Catch Grains/SCF, dry, x 10-3	5.23	3.13	6.27	3.84	5.51	3.58
(c) Particulates from #1 Sump Water sample grains/SCF, x 10-3	1.48		1.31		1.81	
Particulate Removal Efficiency						
Based on air sample (a), %	45.5		42.2		37.6	
Based on air sample (b), %	40.3		38.8		35.1	
Based on total (air and water, a+c), %	58.3		53.2		54.1	
Based on total (air and water, b+c), %	53.4		49.3		51.1	
Entrained Water Removal, %	33.7		33.4		43.5	

TABLE B-17. J-52 ENGINE DATA USING HEILE PACKING

	INLET	OUTLET	INLET	OUTLET	INLET	OUTLET
Date	1-14	1-14	1-25	1-25	1-28	1-28
No. ft. of packing	3		3		3	
Engine operating condition	NR		NR		NR	
Flow at #1 Sump gal./min.	16.4		15.3		16.6	
Flow at #2 Sump gal./min.	.4		53.0		71.5	
Vol. of dry gas sampled, SCF	85.70	75.29	83.43	69.59	83.20	68.22
Stack flow rate, SCFM, dry	8066.0	6813.0	7755.9	6578.6	7963.1	6537.3
Stack gas velocity, at stack conditions, f.p.m.	662.4	536.4	650.5	493.8	668.4	481.8
Moisture, % by volume	16.8	13.5	17.9	10.5	17.5	8.8
Stack gas temp. degree F.	128.6	125.4	130.8	115.4	130.6	112.8
Isokinetic, %	99.4	103.3	100.6	98.9	97.7	97.6
Particulate Results						
(a) Probe and filter catch Grains/SCF, dry, x 10-3	5.23	3.03	5.45	2.55	4.02	2.03
(b) Total Catch Grains/SCF, dry, x 10^{-3}	5.73	3.54	5.74	2.77	4.03	2.64
(c) Particulates from #1 Sump Water sample grains/SCF, x 10-3	1.64		1.67		2.05	
Particulate Removal Efficiency						
Based on air sample (a), %	42.1		53.3		49.4	
Based on air sample (b), %	38.3		51.8		34.5	
Based on total (air and water, a+c), %	55.9		64.2		66.5	
Based on total (air and water, b+c), %	52.0		62.7		56.6	
Entrained Water Removal, %	48.1		68.4		88.6	

B-7. DATA SUMMARY

Source: "A Study of Means for Abatement of Air Pollution Caused by Operation of Jet Engine Test Facilities," United Engineers and Constructors, Inc. Report, Naval Facilities Engineering Command Contract N00025-72-C-0037, August 1973.

Unit Tested

Location	North Island NARF, San Diego, CA
Date Tested	Approximately August 1972
Cell Type	Type A

Engine Tested

Unit	J79-10 and J79-17
Duty Cycle	Idle, military, afterburner

Test Method

Probe Location	Bottom of JETC stack
Number of Points	One point
Gaseous	
Probe Type	
NO_x	Chemiluminescence
CO	Nondispersive infrared analyzer
THC	Flame ionization detector

Emissions Data

DATA SUMMARY TABLE[a]

Pollutant / Power Level	Emissions, lbs/10^6Btu		
	Idle	100%	Afterburner
NO_x	0.1	0.8	0.37
CO	2.3	0.3	1.0
THC as CH_4	0.43	0.08	1.2

[a] Average data for 11 tests on different J79-10 and J79-17 engines

B-8. DATA SUMMARY

Source: "Results of Air Samples from Electrostatic Precipitator," Memorandum on Electrostatic Precipitator Air Sampling Carried out by United Engineers and Constructors, Inc. for SOUDIVNAVFAC, June 1975.

Unit Tested

Location	Jacksonville NARF, Blackpoint No. 1
Date Tested	April 17 - April 18, 1975
Cell Type	Type A
Stack Area	Model scrubber, ~16 ft^2
Pollution Control Equipment	Electrostatic precipitator

Engine Tested

Unit	J79
Duty Cycle	Normal rated

Test Method

Particulates	
Method	EPA Method 5, dry
Probe Location	Upstream and downstream of precipitator
Isokinetic	Yes

Emissions Data	Table B-18

TABLE B-18. J-79 ENGINE DATA WITH ELECTROSTATIC PRECIPITATOR

	INLET	OUTLET	INLET	OUTLET	INLET	OUTLET
Date	4-17	4-17	4-18 AM	4-18 AM	4-18 PM	4-18 PM
Flow at #1 Sump gal./min.	9.66		9.89		9.61	
Vol. of dry gas sampled, SCF	92.79	81.66	87.99	83.31	84.27	84.82
Stack flow rate, SCFM, dry	9276.0	8149.4	8404.3	7621.5	8607.6	7920.2
Stack gas velocity, at stack conditions, f.p.m.	763.8	665.8	703.8	620.5	698.0	698.3
Moisture, % by volume	15.75	15.15	17.13	14.89	16.66	15.39
Stack gas temp. degree F.	132	131	132	131	132	131
Isokinetic, %	97.5	97.6	102.0	106.0	95.0	104.3
Particulate Results						
(a) Probe and filter catch Grains/SCF, dry, x 10^{-3}	6.17	2.90	3.48	1.05	3.14	1.05
(b) Total Catch Grains/SCF, dry, x 10^{-3}	7.30	3.54	3.92	1.20	3.21	1.27
(c) Particulates from #1 Sump Water sample grains/SCF, x 10^{-3}	5.41		5.64		5.14	
Particulate Removal Efficiency						
Based on air sample (a), %	53.0		69.8		66.6	
Based on air sample (b), %	51.5		64.9		60.4	
Based on total (air and water, a+c), %	74.9		88.5		87.3	
Based on total (air and water b+c), %	72.1		86.8		84.8	
Entrained Water Removal, %	11.5		44.8		22.7	

B-9. DATA SUMMARY

Source: "Plume Opacity and Particulate Emissions from a Jet Engine Test Cell," Grimms, B. C., Masters Thesis, University of California, Davis, March 1975.

Unit Tested

Location	McClellan AFB, Sacramento, CA
Date Tested	1975
Cell Type	Modififed reciprocating engine test cell
Stack area	700 sq ft
Stack Height	~15 ft

Engine Tested

Unit	J57-21, J75
Duty Cycle	Idle, military, afterburner

Test Method

Particulates	
Probe Type	EPA Method 5
Method	Dry
Probe Location	Stack exit
Number of Points	Two points
Isokinetic	Attempted
Opacity Measurement Type	Lear-Siegler RM-4 optical transmissometer

Emissions Data	Tables B-19, B-20

TABLE B-19. PARTICULATE MASS CONCENTRATION

FUEL FLOW, LB/HR	CONCENTRATION, Mg/M^3	SUBMICRON CONCENTRATION, Mg/M^3	SUBMICRON CONCENTRATION, %	SAMPLING LOCATION	VELOCITY AT SAMPLING PT., FT/SEC	SAMPLE RATE, % ISOKINETIC	OPACITY %
1,000	2.20	1.85	84	7,5	11.8	81	2.5
1,020	0.15	0.15	100	5,1	4.3[b]	299	3.5
2,500	1.95	1.61	82.5	4,4	10.9	79.4	12
2,500	2.46	—[a]	—	7,6	20.1	96	11
5,000	5.28	4.51	85.5	7,1	12.7	33.9	28
5,000	4.79	—	—	1,6	26.2	72.6	27
8,620	6.08	5.53	91	7,5	46.8	118.7	36.5
8,650	6.34	5.26	83	7,5	42.9	82.6	36.5
8,785	5.26	5.00	95.5	5,1	13.5	195.0	36.3
8,550	6.45	4.97	77	7,5	46.1	160.2	35
13.400[c]	.10.4	6.45	62	7,5	49.8	111.9	36[d]

a. not measured b. variable between -5 and +10 fps c. J-75 d. adjusted for effects of cooling water

TABLE B-20. PARTICULATE EMISSIONS

Fuel Flow lb/hr	Emission Rate Kg/Hr	Emission Factor lb/1000 lb. fuel	Emission Factor[a] lb/10^6 BTU
1,000	0.685	1.51	0.08
1.020	0.042	1.09	0.005
2,500	1.27	1.15	0.062
2,500	1.60	1.41	0.075
5,000	4.99	2.20	0.118
5,000	4.89	2.15	0.115
8,620	6.68	2.19	0.117
8,650	7.74	1.98	0.106
8,785	5.42	1.36	0.073
8,550	7.65	1.97	0.106
13,400	12.3	2.02	0.108

a. based on 18,644 BTU/lb of fuel from 1967 CRC Fuel analysis

B-10. DATA SUMMARY

Source: "Gas Turbine Engine Particulate Measurement Technology," CRC Program, Klarman, A. F., NAPTC-663, February 20, 1973.

Unit Tested

Location	Trenton NAPTC
Date Tested	June 19, 1973
Stack area	28 sq ft
Stack Velocity	Idle ~95 fps, normal rated ~325 fps
Pollution Control Equipment	Ferrocene fuel additive in some runs

Test Method

Particulates	LA AND EPA Methods
Probe Type	
Method (wet & dry)	LA method actually caught less particulate Data lacks repeatability 90 to 40 percent deviation
Probe Location	Exhaust tailpipe, stack exit
Number of Points	15 exhaust tailpipe, 6 stack exit
Isokinetic	Yes
Opacity Measurement Type	SAE smoke number ARP 1179
Gaseous	
Probe Type	Eight points based on EPA standards
NO_x	ARP 1256 chemiluminescence
CO	ARP 1256 nondispersive infrared
UHC	ARP 1256 flame ionization detector
CO_2	ARP 1256 nondispersive infrared

Engine Tested

Unit	J57
Duty Cycle	Idle, normal rated

Emissions Data

Tables B-21 through B-26

GASEOUS DATA SUMMARY TABLE

	Uncontrolled, ppm	
	Idle	Normal Rated
THC	119	15

TABLE B-21. ENGINE AND AMBIENT CONDITIONS

RUN	1	2	3a	3b	4	5	6
Ambient Conditions							
Barometer (in Hg)	30.11	30.11	30.07	30.05	29.96	30.02	29.96
Temperature							
Dry Bulb (°F)	72	81	74	80	86	71	71
Wet Bulb (°F)	69	71	72	75	76	68	67
Humidity (gr/lb Dry Air)	102	98	115	123	119	98	93
Engine Conditions							
Power Mode	Idle	Idle	Normal Rated	Normal Rated	Normal Rated	Normal Rated	Normal Rated
Air Flow (lb/sec)	41.3	41.0	115.8	113.7	110.1	119.4	119.5
Fuel Flow (lb/hr)	1077	1088	5100	4964	4811	5100	5168
f/a	0.00723	0.00737	0.0122	0.0121	0.0121	0.0119	0.0120
Exhaust Gas Temperature (°F)	583	599	900	895	900	898	902
Ferrocene Concentration (g/l JP-5)	-	-	-	-	-	0.43	0.42
Run Time (min)	-	60	38	26	42	41	54

TABLE B-22. EPA SAMPLING TRAIN

RUN	FILTER CATCH (mg)	PROBE AND LINE WASHINGS (mg)	TOTAL PARTICULATES (mg)	TOTAL VOLUME (ft^3)	TOTAL SAMPLED (liters (l))	PARTICULATE CONCENTRATIONS (grains/ft^3)	PARTICULATE CONCENTRATIONS (mg/l)	PERCENT DEVIATION $\frac{(A - B)\ 100^2}{\text{AVG (AB)}}$
Tailpipe								
1 (Idle)	24.0	108.7	132.7	51.47	1457.75	0.0398	0.0910	176
2 (Idle)	7.4	62.8	70.2	14.09	399.10	0.0764	0.1759	
3 (NR)	41.9	89.5	131.4	4.05	114.60	0.5006	1.1466	147
4 (NR)	35.8	19.0	54.8	11.17	316.30	0.0757	0.1732	
5 (NR with Ferrocene)	19.8	18.7	38.5	8.17	231.50	0.0727	0.1663	70
6 (NR with Ferrocene)	20.3	13.0	33.3	14.79	418.80	0.0347	0.0795	
Stack								
1 (Idle)	7.0	35.4	42.4	75.71	2144.15	0.0086	0.0198	11
2 (Idle)	11.2	30.7	41.9	66.85	1893.23	0.0097	0.0221	
3 (NR)	10.2	35.8	46.0	33.69	954.12	0.0211	0.0482	117
4 (NR)	4.8	7.0	11.8	33.36	944.77	0.0054	0.0125	
5 (NR with Ferrocene)	11.0	4.1	15.1	34.40	974.23	0.0068	0.0155	16
6 (NR with Ferrocene)	8.3	4.8	13.1	35.13	994.90	0.0058	0.0132	

TABLE B-23. LA SAMPLING TRAIN

	PARTICULATES							TOTAL				PERCENT DEVIATION
RUN	WATER (mg)	SOLUBLE. (mg/1) (X10-3)	SOLVENT (mg)	SOLUBLE (mg/1) (X10-3)	INSOLUBLE (mg)	(mg/1) (X10-3)	TOTAL PARTICULATES (mg)	VOLUME (ft^3)	SAMPLED (liters (1))	PARTICULATE CONCENTRATIONS (grains/ft^3)	(mg/1)	$\frac{(A - B)\ 100}{AVG\ \ (AB)}$
Inlet												
1	4.9	2.50	23.4	11.9	3.9	2.00	32.2	69.25	1960.9	0.0072	0.0164	103
2	4.4	2.72	2.6	1.61	1.4	0.86	8.4	57.14	1618.0	0.0023	0.0052	
3	3.6	3.76	3.9	4.08	2.1	2.20	9.6	33.77	956.2	0.0044	0.0100	9
4	2.0	2.55	2.6	3.32	2.5	3.19	7.1	27.67	783.5	0.0040	0.0091	
5	0.0	0.00	3.3	4.47	0.0	0.00	3.3	26.10	739.0	0.0020	0.0045	86
6	0.0	0.00	1.7	1.51	0.3	0.27	2.0	39.84	1128.1	0.0008	0.0018	
Stack												
1	19.3	11.2	6.8	3.95	9.1	5.29	35.2	60.77	1720.8	0.0089	0.0205	2
2	15.1	8.15	5.1	2.75	18.4	9.93	38.6	65.46	1853.6	0.0091	0.0208	
3	7.1	5.76	9.0	7.29	15.3	12.4	31.4	43.58	1234.4	0.0111	0.0254	13
4	10.1	13.6	3.2	4.32	8.2	11.1	21.5	26.16	740.7	0.0127	0.0290	
5	4.6	6.93	1.8	2.71	2.1	3.16	8.5	23.45	664.0	0.0056	0.0128	-
6	-	-	-	-	-	-	-	29.99	849.2	-	-	
Tailpipe												
1	39.5	22.0	57.2	31.8	21.4	11.9	118.1	63.55	1799.5	0.0287	0.0656	25
2	28.2	18.8	39.1	26.0	9.0	6.00	76.3	53.01	1501.0	0.0222	0.0508	
3	17.6	-	5.5	-	39.8	-	62.9	-	-	-	-	-
4	7.5	6.70	6.3	5.63	27.2	24.3	41.0	39.53	1119.3	0.0160	0.0366	
5	21.7	19.3	18.5	16.4	12.9	11.4	53.1	39.80	1127.0	0.0205	0.0471	36
6	19.1	13.1	7.7	5.29	21.1	14.5	47.9	51.40	1455.4	0.0144	0.0329	

TABLE B-24. COMPARISON OF ENGINE AND STACK MEASUREMENTS

		ENGINE	STACK	RATIO (E/S)
CO_2 (%)	IDLE	1.28	0.48	2.66
	NR	2.53	0.80	3.16
THC (ppm)	IDLE	295	119	2.48
	NR	25	15	1.66
EPA (mg/l) ($X10^2$)	IDLE	9.35	2.10	4.45
	NR	17.32	3.04	5.68
	NR (Ferrocene)	12.29	1.44	8.53
LA (mg/l) ($X10^2$)	IDLE	5.82	2.07	2.81
	NR	3.66	2.72	1.35
	NR (Ferrocene)	4.00	1.28	3.13

TABLE B-25. COMPARISON OF ENGINE AND STACK PARTICULATE BREAKDOWN FOR LA METHOD

	ENGINE	STACK	RATIO	
Water Soluble ($X10^{-3}$) (mg/l)				
1	22.0	11.2	1.96	
2	18.8	8.15	2.31	
3	-	5.75	-	
4	6.70	13.6	.49	
5	19.3	6.93	2.78	
6	13.1	-	-	
AVG				1.89
Solvent Soluble				
1	31.8	3.95	8.05	
2	26.0	2.75	9.45	
3	-	7.29	-	
4	5.63	4.32	1.30	
5	16.4	2.71	6.05	
6	5.29	-	-	
AVG				6.21
Insoluble				
1	11.9	5.29	2.25	
2	6.00	9.93	.60	
3	-	12.4	-	
4	24.3	11.1	2.19	
5	11.4	3.16	3.61	
6	14.5	-	-	
AVG				2.16
TOTAL AVERAGE				3.42

TABLE B-26. REDUCTION IN PARTICULATES BY FERROCENE

	ENGINE	STACK
EPA (mg/l) - without	17.32	3.04
- with	12.29	1.44
increase/(decrease) (%)	(29)	(53)
LA (mg/l) - without	3.66	2.72
- with	4.00	1.28
increase/(decrease) (%)	9	(53)

B-11. DATA SUMMARY

Source: "Aircraft Engine Emissions Catalog," Aircraft Environmental Support Office, Naval Air Rework Facility, Naval Air Station, North Island, San Diego, California

Unit Tested

Location	Number 10, Naval Air Rework Facility, Naval Air Station, North Island, San Diego, California
Stack Area	9 sq ft

Engine Tested

Unit	T64-GE-6B, T64-GE-413, T58-GE-8F/10
Duty Cycle	Idle, 75 percent, Shaft Horsepower, Military

Test Method

Particulates	
Probe Type	Radar high volume sampler
Probe Location	Stack exit
Number of Points	Two or three points
Isokinetic	Yes
Gaseous	
Probe Type	
NO_x	Chemiluminescence
CO	Nondispersive infrared
Total hydrocarbons	Flame ionization

Emissions Data

DATA SUMMARY TABLE

	T64-GE-6B			T64-GE-413		
	Idle	75%	Military	Idle	75%	Military
Fuel Flow (lb/hr)	337	1039	1390	267	1487	1908
NO_x (lb/1000 lb fuel)	4.0	8.9	11.2	3.1	9.8	11.8
CO (lb/1000 lb fuel)	48.4	4.7	2.3	47.1	2.2	1.2
UHC (lb/1000 lb fuel)	13.1	0.8	0.7	12.2	0.6	0.5
Particulates (mg/m^3)	2.6	6.3	8.6	5.0	26.4	25.1

DATA SUMMARY TABLE

	T58-GE-8F		
	Idle	75%	Military
Particulates[a] (mg/m^3)	11, 7	20, 36	36, 22
Opacity (Ringlemann)	1/4	1/2	3/4

[a] Two runs at same conditions

Emissions Data

DATA SUMMARY TABLE

	T64-GE-6B			T64-GE-413		
	Idle	75%	Military	Idle	75%	Military
Fuel Flow (lb/hr)	337	1039	1390	267	1487	1908
NO_x (lb/1000 lb fuel)	4.0	8.9	11.2	3.1	9.8	11.8
CO (lb/1000 lb fuel)	48.4	4.7	2.3	47.1	2.2	1.2
UHC (lb/1000 lb fuel)	13.1	0.8	0.7	12.2	0.6	0.5
Particulates (mg/m^3)	2.6	6.3	8.6	5.0	26.4	25.1

DATA SUMMARY TABLE

	T58-GE-8F		
	Idle	75%	Military
Particulates[a] (mg/m^3)	11, 7	20, 36	36, 22
Opacity (Ringlemann)	1/4	1/2	3/4

[a] Two runs at same conditions